ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

SYNTHESIS OF TAD-POLE POLYMERS VIA TRIPLE CLICK REACTIONS

M.Sc. THESIS

Tuba DEDEOĞLU

Department of Polymer Science and Technology

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ÜÇLÜ CLİCK REAKSİYONLARI İLE TAD-POLE POLİMERLERİN SENTEZİ

YÜKSEK LİSANS TEZİ

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Tuba DEDEOĞLU, a **M.Sc.** student of ITU **Graduate School of Science Engineering and Technology** student ID **515101026**, successfully defended the **thesis** entitled "**Synthesis of Tad-Pole Polymers via Triple Click Reactions**", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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FOREWORD

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ABBREVIATIONS

^{1}H NMR : Hydrogen Nuclear Magnetic Resonance Spectroscopy
ATRP : Atom Transfer Radical Polymerization
CH_2Cl_2 : Dichloromethane
$CDCl_3$: Deuterated chloroform
C/LRP : Controlled/Living Radical Polymerization
CuAAC : Copper catalyzed azide-alkyne cycloaddition
DA : Diels-Alder
DMF : *N*,*N*-dimehthylformamide
ε-CL : ε-caprolactone
EtOAc : Ethyl acetate
GPC : Gel Permeation Chromatography
MWD : Molecular Weight Distribution
NMP : Nitroxide Mediated Polymerization
PCL : Poly(ε-caprolactone)
PDI : Polydispersity Index
PEG : Poly(ethylene glycol)
PMDETA : *N, N, N',N'', N''*-Pentamethyldiethylenetriamine
PS : Poly(styrene)
RAFT : Reversible Addition Fragmentation Chain Transfer
ROP : Ring Opening Polymerization
r-DA : retro-Diels-Alder
St : Styrene
TD-GPC : Triple Detector-Gel Permeation Chromatography
TEMPO : 2,2,6,6-Tetramethylpiperidine-*N*-oxyl
THF : Tetrahydrofuran
UV : Ultra Violet

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LIST OF SYMBOLS

λ	**:** Wavelength
$R^{\cdot}$	**:** Radical
nm	**:** Nanometer
[η]	**:** Intrinsic viscosity
R_h	**:** Hydrodynamic radius
C	**:** Concentration
A	**:** Absorbance
k_{act}	**:** Activation rate constant
k_{deact}	**:** Deactivation rate constant
R_p	**:** Rate of polymerization
d_n/d_c	**:** Refractive index increment
K	**:** Mark-Houwink-Sakurada constant
ppm	**:** Parts per million
^oC	**:** Celsius
M	**:** Molarity
M_n	**:** The number average molecular weight
M_w	**:** The weight average molecular weight
M_w/M_n	**:** The molecular weight distribution

SYNTHESIS OF TAD-POLE POLYMERS VIA TRIPLE CLICK REACTIONS

SUMMARY

Complex macromolecules have been prepared in the search for polymers with developed mechanical and physical properties. Cyclic polymers, a class of complex macromolecular structures difficult to synthesize covering tad-pole polymer have been recently obtained by the use of click reactions. The tadpole shaped polymer, which consists of a cyclic polymer as head and a linear polymer as tail.

The ionic polymerizations (anionic or cationic) were the only living systems available until last decade. These systems provide polymers with controlled molecular weight, well-defined chain ends, and low polydispersity. In recent years, the use of controlled/living radical polymerization (C/LRP) methods for the synthesis of complex macromolecules has fast increased because of the variety of applicable monomers and more tolerant experimental conditions than the living ionic polymerization routes require. Reversible addition fragmentation chain transfer (RAFT) polymerization, nitroxide-mediated free radical polymerization (NMP), and metal mediated living radical polymerization often called atom transfer radical polymerization (ATRP) are versatile methods for living radical polymerizations.

Meanwhile, the development of the click reactions particularly, copper (I) catalyzed azide-alkyne cycloaddition (CuAAC), Diels–Alder (DA) and nitroxide radical coupling (NRC) reactions, have provided new synthetic pathways for the preparation of tadpole polymers.

In this study, a trifunctional initiator (**4**) was designed containing anthracene, bromide and OH functionalities and subsequently used as an initiator in ATRP of styrene to yield linear polystyrene (PS) with α-anthracene, OH and ω-bromide terminal groups, of which bromide is later transformed into azide to result in the linear α-anthracene-OH-ω-azide-PS (*l*-α-anthracene-OH-ω-azide-PS). The CuAAC click reaction between *l*-α-anthracene-OH-ω-azide-PS and α-furan-protected-maleimide-ω-alkyne linkage, (**5**) afforded *l*-α-anthracene-OH-ω-maleimide-PS. The cyclization via intramolecular Diels-Alder click reaction of this linear PS and subsequent conversion of the hydroxyl into bromide resulted in the cyclic PS with one bromide located on the ring, (*c*-PS)-Br. Finally, the *c*-PS-Br was clicked with either well-defined TEMPO-terminated poly(ethylene glycol) (TEMPO-PEG) or poly(ε-caprolactone) (TEMPO-PCL) yielding the tadpole polymer, (*c*-PS)-*b*-PEG or (*c*-PS)-*b*-PCL.

ÜÇLÜ CLİCK REAKSİYONLARI İLE TAD-POLE POLİMERLERİN SENTEZİ

ÖZET

Üstün özellikler gösteren ileri polimerik malzemeler büyük ilgi görmektedir. Farklı fiziksel ve mekanik özellikleri bir arada bulunduran blok kopolimerler en çok rağbet gören ileri malzemeler arasındadır. Çeşitli kompleks makromoleküler yapılara sahip olmaları bu polimerlere ileri teknoloji uygulamaları için gereken özgün özellikler kazandırır.

Tad-pole polimerler sentezi zor olan, kompleks makromoleküler yapılı polimer sınıfına ait halkalı polimerlerden olup günümüzde click reaksiyonları kullanılarak elde edilir. Tad-pole polimerler baş tarafı halkalı, kuyruk tarafı lineer olan polimerlerdir.

Halkalı polimerler, kompleks makromoleküler yapıların bir türü olup Q şekilli, tadpole şekilli, alfa şekilli, bisiklik gibi oldukça çeşitli polimerlerin sentezlenmesinde kullanılır. Son zamanlarda bu sentezler genellikle click reaksiyonlar kullanılarak sağlanmaktadır.

Siklizasyon prensibi belirlenmiş olan iki ana yöntemle sınıflandırılır. Birinci yöntem halka-zincir denge kullanımıdır. Bu yöntem pek çok polikondenzasyon ve zincir açılma polimerizasyonlarını içerir. İkinci yöntem ise uçtan uca siklizasyon yöntemidir ki bu yöntemde halkalı polimer $\alpha,\omega-$difonksiyonel lineer öncülerden sentezlenir.

Halkalı polimerlerin eşsiz topolojisi lineer polimerlerle kıyaslandığında farklı fiziksel özellikler gösterir. Mesela, tipik halkalı polimerler aynı molekül ağırlığındaki ve kompozisyondaki lineer polimerden farklı viskoziteye, camsı geçiş sıcaklığına ve yoğunluğa sahiptirler. Ayrıca aynı molekül ağırlığındaki ve kompozisyondaki halkalı ve lineer polimerler birbirlerinden farklı hacim kaplarlar. Eğer bir halkalı polimer bir tekli bağdan parçalanırsa sonuçta oluşacak olan lineer polimer aynı molekül ağırlığında olur ancak hidrodinamik çapı daha büyük olur. Bu sonuç halkalı polimer analiz edildiğinde önemli çıktılar ortaya koyar. Çünkü GPC (Jel Geçirgenlik Kromatografi) aslında polimerlerin hidrodinamik çapını ölçer ve bu doğrultuda doğru molekül ağırlığını verir.

Halkalı polimer sınıfından olan tadpole polimerler üç yöntemle sentezlenirler. Birinci sentez yöntemi, iki tamamlayıcı aktif uçlu polimerin siklizasyonuyla gerçekleşir. Bu tamamlayıcı aktif uçların biri polimer zincirinin sonunda diğeri ise polimer zincirinin ortasındadır. İkinci sentez yöntemi, biri halkalı diğeri lineer olan polimerlerin birleşmesiyle gerçekleşir. Burada hem halkalı hem de lineer polimer bir aktif uca sahiptir ve bu aktif uçlar birbirleriyle etkileşerek tadpole yapılı polimeri oluştururlar. Üçüncü sentez yöntemi de iki ayrı polimerin birleşmesiyle gerçekleşir. Buradaki öncü polimerlerden biri zincir sonunda iki aktif anyon diğeri ise iki aktif katyon bulunduran lineer polimerlerdir ve reaksiyon bu aktif uçların birleşmesiyle

sonuçlanır. Bahsedilen bu sentez yöntemlerinde reaksiyon seyreltik koşullarda gerçekleşir.

Kontrollü kompozisyon ve yapılarda iyi tanımlanmış makromoleküllerin sentezi polimer biliminde yeni bir alan açan iyonik polimerizasyon yöntemlerinin gelişimine kadar kimyagerler için sorun olmuştu. Ancak, iyonik polimerizasyon araştırmalarının gelişimi zorlu işlem koşulları; yüksek saflık ve çeşitli fonksiyonel monomerlerle uyumsuzluk söz konusu olduğundan bazı ciddi engeller ile karşılaşmaktadır. Serbest radikal polimerizasyonu safsızlıklara daha toleranslıdır ve çok çeşitli vinil monomerlerinin polimerleştirilmesi yeteneğine sahiptir fakat en büyük dezavantajı iyonik polimerizasyondaki gibi polimer yapı ve fonksiyonalite kontrolünün aynı derecede mümkün olmamasıdır. Bu nedenle, kaydadeğer çabalar serbest radikal polimerizasyonunu kontrollü bir şekilde gerçekleştirmek için harcanmıştır. Neyse ki, serbest radikal polimerizasyonunundaki devrim herhangi bir zorlu deneysel koşul gereksinimleri olmayan, iyi tanımlanmış makromoleküllerin inşasına erişim kolaylığı sağlayan kontrollü/"yaşayan" radikal polimerizasyon (C/LRP) yöntemlerinin gelişimlerine yol açmıştır. Günümüzde, en etkili ve en sık kullanılan üç C/LRP yöntemi: kararlı serbest radikal polimerleşmesi (SFRP) veya en sık kullanılan ifadesi ile nitroksit ortamlı radikal polimerleşmesi (NMP), atom transfer radikal polimerleşmesi (ATRP), ve tersinir eklenme-ayrılma zincir transfer polimerleşmesidir. Sonuç olarak, bu yöntemlerin polimer sentezinde geniş bir yelpazede yaygın olarak kabulu ve yararlanılması iyi tanımlanmış makromoleküllerin kontrollü kompozisyon, yapı ve fonksiyonalitede yapılmasındaki sınırsız potansiyellerine dayanır.

Kontrollü /yaşayan polimerizasyon tekniklerinden biri olan ATRP kendinden önceki kontrollü radikal polimerizasyon yöntemlerinden (iyonik ,kararlı serbest radikal polimerizasyonu gibi), karmaşık polimer yapıları üretimine izin vermesi ile ayrılır.Bu polimerizasyon yöntemi, sıcaklık gibi reaksiyon parametrelerinin kontrolü ile kolayca durdurulup yeniden başlatılabilir. ATRP'den önce ortaya çıkan kontrollü polimerleşme yöntemlerinde her çeşit monomer kullanılamamasına karşın, ATRP mekanizmasında geniş bir monomer yelpazesine kullanılabilir. Kontrollü ve düzenli büyüyen polimer zinciri ve düşük molekül ağırlığı dağılımı (*polidispersite*), ATRP mekanizması sırasında kullanılan metal bazlı katalizör sayesinde elde edilir.

Sharpless ve çalışma arkadaşları tarafından ortaya çıkarılan 'Click Kimyası' yüksek oranda ürün eldesi, fonksiyonel gruplara karşı olan toleransları ve seçiciliği ile önemli bir yeri vardır. Nükleofilik zincir açılma reaksiyonları, non-aldol karbonil kimyası, karbon–karbon çoklu bağlara tiol katılnası (tiolen ve tiolin) ve siklokatılma reaksiyonları gibi pek çok prosesi sahiptir. Kimyacılar arasında en çok bakır(I)-katalizli azid-alkin (CuAAC) ve Diels-Alder (DA) siklokatılma reaksiyonları kullanılmaktadır. Cu(I) katalizli Huisgen 1,3-dipolar siklik katılması da terminal alken ve alkil azid arasında baz katalizörlü oda sıcaklığında gerçekleşen bir reaksiyondur. Bu reaksiyon molekülleri birbirine bağlamada kullanılabilir. Diels-Alder reaksiyonları ise konjuge bir dien ile dienofil bileşiğinin siklo katılması olarak bilinir.

Günümüzde, "Click Kimyası" terimi altında sınıflandırılan Diels-Alder (DA) ve bakır(I)-katalizli azid-alkin siklokatılma (CuAAC) tepkimeleri blok kopolimerlerden karmaşık makromoleküler yapılara kadar değişen birçok polimerik malzemenin sentezinde başarılı bir şekilde uygulandı ve çeşitli topolojide polimerlerin eldelerinde güçlü bir alternatif yöntem olarak ortaya çıktı.

Buna ek olarak , yine "Click Kimyası" terimi altında sınıflandırılabilinen nitroksit radikal birleşme reaksiyonları (NRC), moleküllerin birbirlerine seçici ve hızlı bir şekilde bağlanmasını sağlamak amacıyla molekül uçlarında TEMPO ve türevlerinin kullanıldığı bir tepkimedir. TEMPO uç fonksiyonlu polimer malzemeler ışık, şok ve ısı değişikliklerine daha az duyarlı olduklarından, azid uç grubu taşıyan polimerlere göre daha kararlıdırlar. Farklı topolojilere uygulanabilirliği ve yüksek verimlilikleri nedeniyle iyi tanımlanmış polimerlerin sentezi için potansiyel bir click reaksiyonu olarak kabul edilir.

Kontrollü/yaşayan polimerleşme ve click kimyası tekniklerinin gelişmesi sonucunda kompleks makromoleküler yapılarının topoloji, kompozisyon ve işlevselliklerinin pek çok yönleri tanımlanmış olur. Böylece iyi tanımlanmış farklı topolojide polimerik maddelerin sentezlenmesi sağlanır. Yani polimerler lineer, yıldız, halkalı, dallı, jel, fırça polimerle rgibi oldukça geniş topolojide sentezlenir.

Bu noktadan hareketle bu tezde Kontrollü /yaşayan polimerizasyon tekniklerinden ATRP ve CuAAC, DA, NRC click reaksiyonlarının birlikte kullanılmasıyla iyi tanımlanmış Tadpole yapılı blokopolimer sentezi tanımlanmıştır.

Bu çalışmada, antrasen, brom ve OH fonksiyonlarını içeren üç fonksiyonlu bir başlatıcı dizayn edilmiştir (**4**) ve daha sonra α-antrasen ile lineer polistiren elde etmek için stirenin ATRP' sinde başlatıcı olarak kulanılmıştır, OH ve ω-brom uç gruplardan brom, lineer α-anthrasen-OH-ω-azid-PS (*l*-α-anthrasen-OH-ω-azid-PS) olarak sonuçlandırılması için azide dönüştürülmüştür. CuAAC click reaksiyonu *l*-α-anthrasen-OH-ω-azid-PS ve α-furan-korumalı-maleimid-ω-alkin (**5**) arasında bağ kurarak *l*-α-anthracen-OH-ω-maleimid-PS oluşumunu sağlamıştır. Bu lineer PS'in intramoleküler Dies-Alder click reaksiyonuyla halka kapanması sağlanmış ve sonra hidroksil broma dönüşerek halka üzerinde bir bromlu halkalı PS ile sonuçlanmıştır (*c*-PS)-Br. En sonunda, *c*-PS-Br ya iyi tanımlı TEMPO-uçlu poly(etilen glikol) (TEMPO PEG) ya da poly(ε-kaprolakton) (TEMPO PCL) ile clicklendirilerek tadpole polimer, (*c*-PS)-*b*-PEG veya (*c*-PS)-*b*-PCL, elde edilmiştir. Elde edilen polimerin ve öncülerinin yapıları ^{1}H-NMR, TD-GPC ve UV spektofotometre yardımıyla aydınlatılmıştır.

Ürünün ve öncülerinin karakterizasyonu ^{1}H-NMR spektrumları ile yapılmıştır. UV spektofotometresi ile de DA etkileşimi hesaplanmıştır. TD-GPC ile DA öncesi lineer polimerin ve sonrası halkalı polimerin mutlak molekül ağırlığı, dn/dc (mL/g) değeri, intrinsik viskozite ([η]), hidrodinamik yarıçap (R_h) değerleri ölçülmüştür. GPC ile sentezlenen tüm polimerlerin molekül ağırlıkları ve polidispersiteleri ölçülmüştür.

Sonuçta elde edilen tadpole yapılı polimerlerin ve halkalı ve lineer öncülerinin GPC overlay görüntüleri monomodal bir dağılım göstermektedir. Bu görüntülerde tadpole yapılı polimerlerin öncülerine göre daha yüksek molekül ağırlıklı alanda çıkmasından dolayı polimerleşmenin gerçekleştiği net bir şekilde görülmektedir. Bu çalışmada çeşitli kompozisyonlarda tadpole yapılı polimerlerin basit ve etkin bir yolla elde edilmesi için kullanılabilecek üçlü click reaksiyon yöntemi belirtilmiştir.

1. INTRODUCTION

Polymer properties are mainly influenced by the chemical composition, functionality, molecular weight and topology of the constituting macromolecules.[1] Therefore, the synthesis of well-defined complex macromolecular structures, such as stars, dendrimers, graft and cyclic polymers, to control the polymer properties is a key field of study in polymer science [1].

The ionic polymerizations (anionic or cationic) were the only living systems available until recently. These systems provide the polymers with the controlled molecular weight, well-defined chain ends and low polydispersity. In recent years, the controlled/living radical polymerization (C/LRP) techniques for the synthesis of complex macromolecules has fast increased because of the variety of applicable monomers and more tolerant experimental conditions than the living ionic polymerization techniques require [2-4]. The reversible addition fragmentation chain transfer [5] (RAFT) polymerization, the nitroxide-mediated radical polymerization [6] (NMP), and the metal mediated living radical polymerization often called atom transfer radical polymerization [7-9] (ATRP) are versatile methods for the living radical polymerizations.

Nitroxide radical coupling (NRC) reaction is considered as a potential click reaction due to its high efficiency and orthogonality in the synthesis of well-defined polymers with different topologies. The NRC click reaction proceeds between a halide- and a 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO)-terminated polymers in the presence of CuBr and ligand under mild reaction temperature based on the ATRP mechanism [10].

The “click chemistry” concept was introduced by Sharpless and coworkers in 2001 [11]. Selected reactions were classifield as click chemistry if they were modular, stereospecific, wide in scope, resulted in high yields, and generated only safe byproducts. Several efficient reactions such as copper (I) catalyzed azide-alkyne cycloaddition (CuAAC), Diels-Alder (DA), thiol additions to double bond (thiol-ene) and also nitroxide radical coupling (NRC) can be classified under this term. Since

their fast growth, click chemistry strategies have been rapidly integrated into the field of macromolecular engineering and extensively been used in the synthesis of polymers ranging from linear to complex structures.

Cyclic polymers, a class of complex macromolecular structures difficult to synthesize covering tadpole, pseudocyclic (Q shaped), bicyclic (eight shaped) and knotted (alpha shaped) polymers have been recently obtained by the use of click reactions [12-39].

The cyclization principle can be classified into two main methods as indicated. One is the utilization of the ring-chain equilibrium that occurs in many polycondensation and ring opening polymerization. Another is the end-to-end cyclization method that can be used for synthesizing cyclic polymers from α,ω–difunctional linear precursors.

The tadpole shaped polymer, which consists of a cyclic polymer as head and a linear polymer as tail. There are three general synthetic strategies. a) Cyclization of linear polymers with two complementary reactive functions sited at the end and the middle of chain, respectively, under dilute condition; b) couple reaction of one reactive group in cyclic polymer with one terminal function of linear polymer; c) couple reaction of two reactive anions (or cations) at both end of the chain with two reactive cations (or anions) at one end of the linear polymer chain [40].

In this study, abovementioned Diels-Alder macromolecular cyclization of anthracene with maleimide end-groups is extended to the preparation of tad-pole polymers. The use of CuAAC click reaction allowed us to prepare a well-defined linear heterotelechelic PS precursor with anthracene and hydroxyl at α-end and maleimide at ω-end. The cyclization of this linear heterotelechelic PS precursor via an intramolecular Diels-Alder click reaction and subsequent transformation of the hydroxyl group with bromide yielded a cyclic PS with one bromide on the ring, (*c*-PS)-Br. The resulting (*c*-PS)-Br was further reacted with a TEMPO-terminated-poly(ethylene glycol) (PEG) or -PCL to yield related tad-pole polymers, (*c*-PS)-*b*-PEG and (*c*-PS)-*b*-PCL, via NRC reaction (Figure: 1.1).

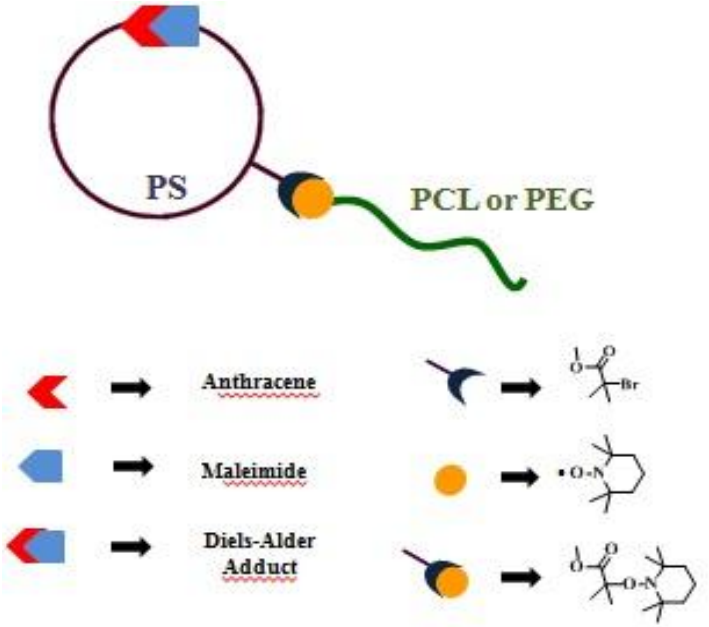


Figure 1.1: Synthesis of tad-pole polymers, (*c*-PS)-*b*-PEG and (*c*-PS)-*b*-PCL, via NRC reaction.

2. THEORETICAL PART

2.1 Controlled/ ‘‘Living” Polymerizations

A living polymerization is defined as a chain polymerization without chain transfer and chain termination as indicated by Szwarc. Well-defined polymers, can only be synthesized by living ionic polymerizations or controlled/ “living” radical polymerization (C/LRP) methods [41]. Until recently, ionic polymerizations (anionic or cationic) were the only living techniques that efficiently controlled the structure and architecture of vinyl polymers. These polymerization techniques ensure low polydispersity materials, controlled molecular weight and defined chain ends but they are not useful for the polymerization and copolymerization of a wide range of functionalized vinylic monomers [42]. Furthermore, these techniques require stringent reaction conditions and pure reagents. To overcome all these limitations polymer chemists developed new concepts. These new concepts are often called controlled radical polymerization, living radical polymerization, control/“living” radical polymerization [43, 44].

Living polymerization provides end-group control and enables the synthesis of block copolymers by sequential monomer addition. However, it does not necessarily provide polymers with molecular weight (MW) control and narrow molecular weight distribution (MWD). To obtain well defined polymers the initiator should be consumed at early stages of polymerization and that the exchange between species of various reactivities should be at least as fast as propagation [45-47].

2.1.1 Controlled/ ‘‘Living” radical polymerizations

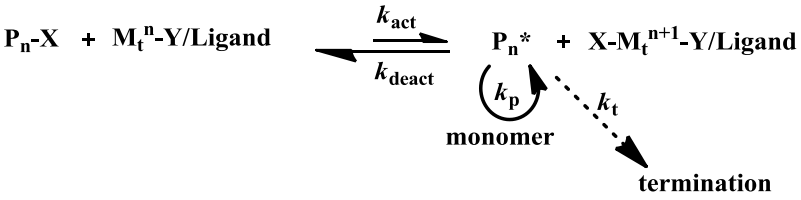
Living free radical polymerizations have attained a tremendous following in polymer chemistry. A great deal of effort has been made to develop and understand different living free radical polymerization (LFRP) methods. Georges and co-workers first introduced true nitroxide mediated polymerization (NMP) in 1993, Matyjaszewski

and Sawamoto developed metal catalzed (Cu, Ru) living radical polymerization also called atom transfer radical polymerization (ATRP) in 1995, and Moad, Rizzardo

and Thang reported reversible addition-fragmentation chain transfer polymerization (RAFT) in 1998 [48, 49, 50, 51].

2.1.1.1 Atom transfer radical polymerization (ATRP)

Atom transfer radical polymerization (ATRP) is a living radical polymerization process, which is consisting of the monomer, initiator, and catalyst composed of transition metal species with any suitable ligand. ATRP, which is the most versatile method of the controlled radical polymerization system, uses a wide variety of monomers, catalysts, solvents, and reaction temperature. ATRP is one of the most convenient methods to synthesize well-defined low molecular weight polymers [52].



(2.1)

Equation 2.1 represents the general mechanism of ATRP. The radicals the propagating species Pn*, are generated through a reversible redox process catalyzed by a transition metal complex. Radicals react reversibly with the oxidized metal halide complexes, $X–M_t^{n+1}$ / ligand, the deactivator, to reform the dormant species and the activator. These processes are fast, and the dynamic equilibrium that is established favors the dormant species. By this way, all chains can begin growth at the same time, and the concentration of the free radicals is quite low, resulting in reduced amount of irreversible radical-radical termination. Since the deactivation rate constant is substantially higher than that of the activation reaction $K_{eq} = K_{act} / Kd_{eact} \sim 10^{-7}$; each polymer chain is protected by spending most of the time in the dormant state, and thereby the permanent termination via radical coupling and disproportionation is substantially reduced. Polymer chains grow by the addition of the free radicals to monomers in a manner similar to a conventional radical polymerization, with the rate constant of propagation, k_p. Termination reactions (k_t) also occur in ATRP, mainly through radical coupling and disproportionation; however, in a well-controlled ATRP, only several percents of the chains become dead via termination [53]. Polydispersities in ATRP decrease with conversion, with the rate constant of deactivation and also with the concentration of deactivator. The

molecular conversion and the amount of initiator used, DP = $\Delta[M]/[I]_0$; polydispersities are low, $M_w / M_n < 1,3$ [54].

In ATRP process can be used a variety of monomers, allowing control during the polymerization of styrenics [55], (meth)acrylates [56], acrylamides [57, 58], vinylpyridines [59, 60], and acrylonitrile [61]. Additionally, ATRP has tolerance to many functional groups such as amido, amino, ester, ether, hydroxy, siloxy and others. Having 'free' carboxylic acid funtional monomers are not used for ATRP, since they potentially complexes with the catalyst and disables ATRP, and therefore, presently, it has to be protected. Recent work has shown that monomers bearing ionic substituents such as sodium 4-vinylbenzoate, sodium 4-vinylbenzylsulfonate and 2-trimethylammonioethyl methacrylate methanesulfonate and triflate, and dimethylaminoethyl methacryate can be polymerized directly [62].

The initiator posses an important role to determine the number of growing chains. In ATRP, alkyl halides (RX) are typically used as initiators. For the successful polymerization, initiation should be quantitative and faster than propagation. To obtain best controlled polymers over narrow PDI and molecular weight, the halide group, X, should transfer fast between the growing chain and the transition metal complex. So, X must be either bromine or chlorine. Iodine works well for acrylate polymerizations in copper-mediated ATRP [63] but fluorine is not suitable because The carbon–fluorine bond strength is too strong for the fast activation–deactivation.

The catalyst has the main role in ATRP since it determines the position of the atom transfer equilibrium and the dynamics of exchange between the dormant and active species. There are some requirements, using a catalyst in ATRP process [63]. 26 First, the metal center must have at least two oxidation states. Second, the metal center should have enough affinity toward a halogen, also the ligand should complex the metal relatively strongly. ATRP has been successfully worked by a variety of metals, including those from Groups 4 (Ti [64]), 6 (Mo [65-67]), 7 (Re [68]), 8 (Fe [69-72], Ru [73], Os [65]), 9 (Rh [74], Co [56]), 10 (Ni [75, 76], Pd [77]), and 11 (Cu [55, 78]). But complexes of Cu have been found to be the most efficient catalysts in the ATRP.

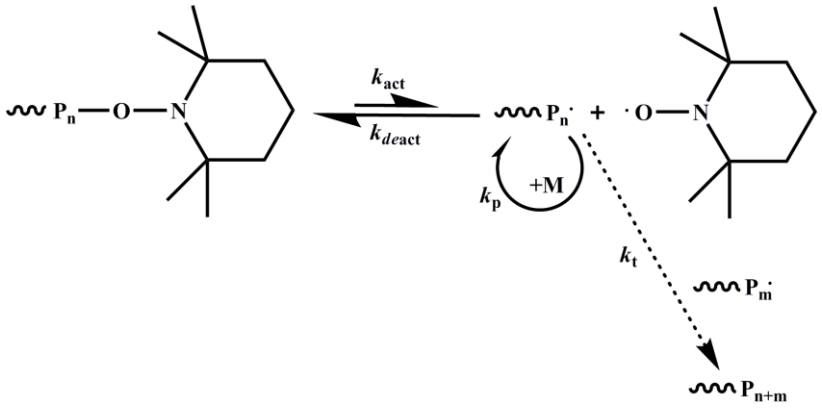
Ligand is the other important component for ATRP system. It helps to solubilize the transition metal salt in the organic media and to adapt the redox potential and

dynamics of exchange between the dormant and active species with atom transfer [79]. The ligand should complex strongly with the transition metal, and also allow expansion of the coordination sphere and selective atom transfer without any side reactions. Commonly employed nitrogen-based ligands used in conjunction with Cu ATRP catalysts include derivatives of bidentate bipyridine (bpy) [78, 80] and pyridine imine [81], tridentate diethylenetriamine (DETA) [82], and tetradentate tris[2-aminoethyl]amine (TREN) [83] and tetraazacyclotetradecane (CYCLAM) [84].

ATRP can be carried out either in bulk, in solution or in a heterogeneous system (e.g., emulsion, suspension). Various solvents such as benzene, toluene, anisole, diphenyl ether, ethyl acetate, acetone, dimethyl formamide (DMF), ethylene carbonate, alcohol, water, carbon dioxide and many others have been used for different monomers. A solvent is sometimes necessary especially when the obtained polymer is insoluble in its monomer [85].

2.1.1.2 Nitroxide mediated radical polymerization (NMP)

Nitroxide–mediated living free radical polymerization (NMP) belongs to a much larger family of processes called stable free radical polymerizations. In this type of process, the propagating species (Pn°) reacts with a stable radical (X°) as seen in equation 2.2. The resulting dormant species (Pn-X) can then reversibly cleave to regenerate the free radicals once again. Once Pn° forms it can then react with a monomer, M, and propagate further. The most commonly used stable radicals have been nitroxides, especially 2,2,6,6-tetramethylpiperidinoxy (TEMPO). The 2,2’,6,6’-tetramethylpiperidine-1-oxyl radical (TEMPO) was used as the nitroxide component in these initial studies. The alkoxyamine is formed in situ during the polymerization process. Shortly thereafter, it was shown that low molecular weight alkoxyamines such as styryl-TEMPO can be used as initiators/regulators for the controlled living radical polymerization of styrene [86]. Although NMP is one of the simplest methods of living free radical polymerization (LFRP), it has many disadvantages. Many monomers will not polymerize because of the stability of the dormant alkoxyamine that forms. Also, since the reaction is kinetically slow, high temperatures and bulk solutions are often required. Also, the alkoxyamine end groups are difficult to transform and require radical chemistry [87].



(2.2)

The chain end functionalization of polymers synthesized by NMP is a significant problem because dormant chains containing alkoxyamines can regenerate terminal radicals which can depolymerize at high temperatures. A very interesting chain end functionalization process has also been discovered by Hawker which involves the controlled monoaddition of maleic anhydride or maleimide derivatives to the alkoxyamine chain end. The alkoxyamine can then be easily eliminated and other functional groups can be introduced. This process relies on the resistance of maleic anhydride or maleimide derivatives to homopolymerize and the ability of the precursor to reform the olefin by elimination of the hydroxylamine [88].

2.1.1.3 Reversible-addition fragmentation chain transfer (RAFT)

The most recent report of a controlled/"living" free radical polymerization has been reported by Haddleton and co-workers as well as Thang et al. Reversible addition-fragmentation chain transfer (RAFT) is achieved by performing a free radical polymerization in the presence of dithio compounds, which act as efficient reversible addition-fragmentation chain transfer agents. Much like the first two routes, the rapid switching mechanism between dormant and active chain ends affords living polymerization character [89].

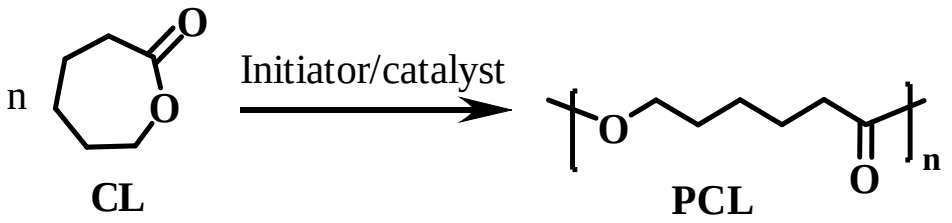
Reversible addition-fragmentation chain transfer (RAFT) incorporates compounds, usually dithio derivatives, within the living polymerization that react with the propagating center to form a dormant intermediate. The dithio compound can release the alkyl group attached to the opposite sulfur atom which can then propagate with the monomer. The greatest advantage to RAFT is the incredible range of polymerizable monomers. As long as the monomer can undergo radical

polymerization, the process will most likey be compatible with RAFT. However, there are many major drawback that arise when using this process. The dithio end groups left on the polymer give rise to toxicity, color, and odor and their removal or displacement requires radical chemistry. Also, the RAFT agents are expensive and not commercially available. Another drawback is that the process requires an initiator, which can cause undesired end groups and produce too many new chains which can lead to increased termination rates [90].

2.1.2 Ring-opening polymerization (ROP)

Aliphatic poly(ester)s receive increasing attention nowadays due to their biodegradable property. Poly(ester)s can be prepared from a wide range of materials with judicious choice of monomer feedstock able to modulate the physio-chemical properties including glass transition temperatures, toughness, stiffness and degradability.

Aliphatic poly(ester)s are prepared through one of two routes: the first is step-growth polycondensation of a hydroxy acid or between a diacid and a diol. The second route is ring-opening polymerization (ROP). It is a unique polymerization process, in which a cyclic monomer is opened to generate a linear polymer, e.g., ROP of ε-caprolactone (CL) (equation 2.3). ROP is a chain polymerization, comprise of a sequence of initiation, propagation and termination, so different from step polymerization. Altough ROP like as living polymerization because of increasing molecular weigth linearly with conversion [91], it differs from chain polymerizations due to reaction kinetics. By this methodology the preparation of high molecular weight aliphatic poly(ester)s is possible while maintaining high levels of control over their molecular characteristics under relatively mild conditions.



(2.3)

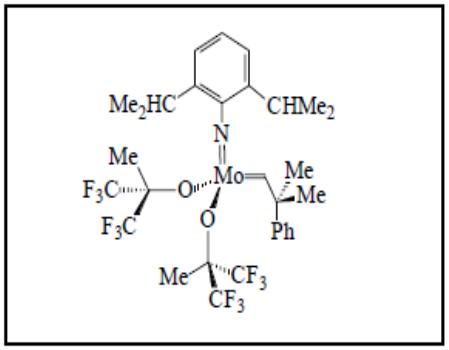
The thermodynamic factors (ΔH, ΔS, ΔG) affecting the ring opening of a cyclic monomer will be due to the relative stability of the linear polymer in comparison to its corresponding monomer [92]. Four or seven membered rings have greater ring

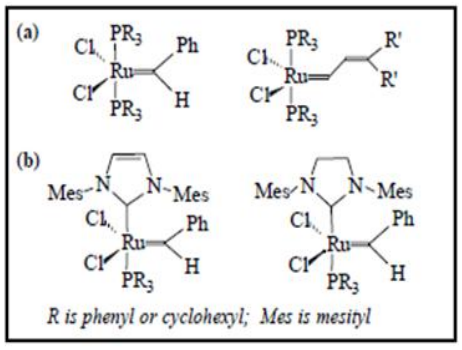
strain in comparison with five or six membered rings and hence there is a greater thermodynamic driving force for their ROP. A series of simple lactones of varying ring size and strain have been investigated. Generally, substituents on the rings decrease the ring strain and thereby the polymerizability of the rings.

2.1.3 Ring-opening metathesis polymerization (ROMP)

Although a relatively new player on the field of polymer chemistry, ring-opening metathesis polymerization (ROMP) has emerged as a powerful and broadly applicable method for synthesizing macromolecular materials. The origins of ROMP can be traced to the mid-1950s when various metals and reagents were combined to uncover new transformations and reactivities involving olefins. However, the rapid rise in popularity and utility of this polymerization technique is the result of extensive work on the identification and isolation of key intermediates involved in the general olefin metathesis reaction. This led to the development of well-defined ROMP catalysts and ultimately enabled the synthesis of a wide range of polymers with complex architectures and useful functions [92].

It was only in 1971 that a metal-carbene intermediate was proposed by Y. Chauvin, to explain – satisfactorily for the first time – the mechanism. This extraordinary mechanistic proposal, rationalising Chauvin's astonishing new observations, was immediately embraced by the metathesis community and prompted studies on metal-carbene initiators culminating in the creation of the molybdenum- alkylidene catalysts by R. R. Schrock and the 1st and 2nd generation of ruthenium-alkylidene catalysts, by R. H. Grubbs, respectevly(equation 2.4) [93].





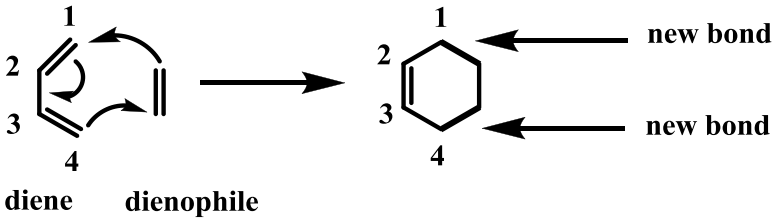
(2.4)

2.2 Click Chemistry

"Click chemistry" is a chemical term introduced by Sharpless in 2001 and describes chemistry tailored to generate substances quickly and reliably by joining small units together [94]. Click chemistry can be summarized only one sentence: Molecules that are easy to make. Sharpless also introduced some criteria in order to fullfill the requirements as reactions that: are modular, wide in scope, high yielding, create only inoffensive by-products, are stereospecific, simple to perform and that require benign or easily removed solvent. Nowadays there are several processes have been identified under this term in order to meet these criterias such as nucleophilic ring opening reactions; non-aldol carbonyl chemistry; thiol additions to carbon–carbon multiple bonds (thiol-ene and thiol-yne); and cycloaddition reactions. Among these selected reactions, copper(I)-catalyzed azide-alkyne (CuAAC) and Diels-Alder (DA) cycloaddition reactions have gained much interest among the chemists not only the synthetic ones but also the polymer chemists. Also atom transfer nitroxide radical coupling (ATNRC) has the attributes of a "click" reaction.

2.2.1 Diels-alder reaction

The Diels-Alder (DA) reaction is a concerted [4π+2π] cycloaddition reaction of a conjugated diene and a dienophile. This reaction is one of the most powerful tools used in the synthesis of important organic molecules. The three double bonds in the two starting materials are converted into two new single bonds and one new double bond to afford cyclohexenes and related compounds (equation 2.5). This reaction is named for Otto Diels and Kurt Alder, who received the 1950 Nobel prize for discovering this useful transformation [95-97].

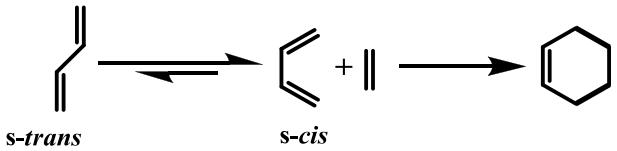


(2.5)

Typically, the DA reaction works best when either the diene is substituted with electron donating groups (like -OR, -NR2, etc) or when the dienophile is substituted with electron-withdrawing groups (like -NO2, -CN, -COR, etc) [98].

2.2.1.1 Stereochemistry of diels-alder reaction

There are stereochemical and electronic requirements for the DA reaction to occur smoothly. First, the diene must be in an s-cis conformation instead of an s-trans conformation to allow maximum overlap of the orbitals participating in the reaction (equation 2.6).



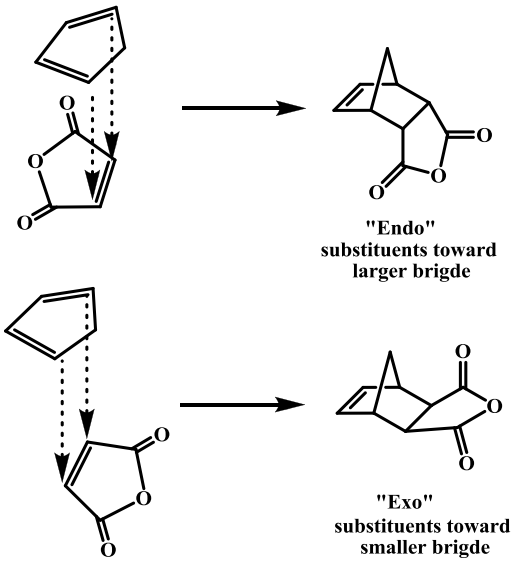
(2.6)

The "s" in s-cis and s-trans refers to "sigma", and these labels describe the arrangement of the double bonds around the central sigma bond of a diene. Dienes often exist primarily in the lower energy s-trans conformation, but the two conformations are in equilibrium with each other. The s-cis conformation is able to react in the DA reaction and the equilibrium position shifts towards the s-cis conformer to replenish it. Over time, all the s-trans conformer is converted to the s-cis conformer as the reaction proceeds.

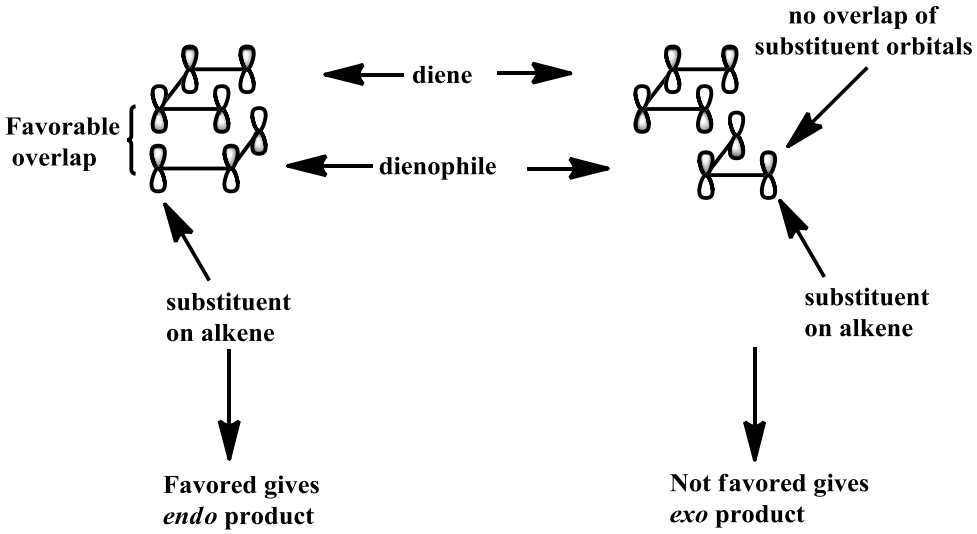
A unique type of stereoselectivity is observed in DA reactions when the diene is cyclic. In the reaction of maleic anhydride with cyclopentadiene, for example, the endo isomer is formed (the substituents from the dienophile point to the larger bridge) rather than the exo isomer (the substituents from the dienophile point away from the larger bridge) (equation 2.7).

The preference for endo–stereochemistry is "observed" in most DA reactions. The fact that the more hindered endo product is formed puzzled scientists until Woodward, Hoffmann, and Fukui used molecular orbital theory to explain that overlap of the p orbitals on the substituents on the dienophile with p orbitals on the diene is favorable, helping to bring the two molecules together [99, 100].

Hoffmann and Fukui shared the 1981 Nobel Prize in chemistry for their molecular orbital explanation of this and other organic reactions. In the illustration below, notice the favorable overlap (matching light or dark lobes) of the diene and the substituent on the dienophile in the formation of the endo product (equation 2.8).



(2.7)



(2.8)

Oftentimes, even though the endo product is formed initially, an exo isomer will be isolated from a DA reaction. This occurs because the exo isomer, having less steric strain than the endo, is more stable, and because the DA reaction is often reversible under the reaction conditions. In a reversible reaction, the product is formed, reverts to starting material, and forms again many times before being isolated. The more stable the product, the less likely it will be to revert to the starting material. If the reaction is not reversible under the conditions used, the kinetic product will be isolated. However, if the first formed product is not the most stable product and the reaction is reversible under the conditions used, then the most stable product, called the thermodynamic product, will often be isolated.

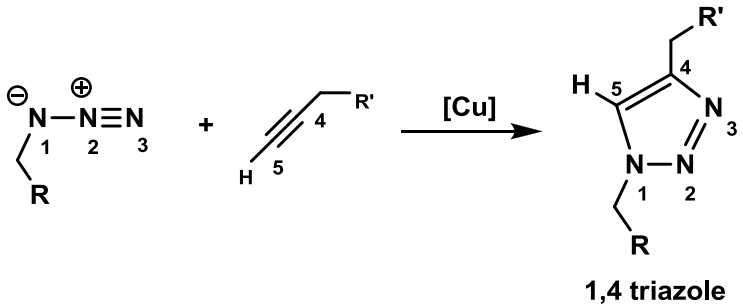
2.2.2 Copper(I)-catalyzed azide-alkyne cycloaddition (CuAAC)

Huisgen's 1,3-dipolar cycloaddition of alkynes and azides yielding triazoles is, undoubtedly, the premier example of a click reaction [101]. Recently, 1,3-dipolar cycloadditions, such as reactions between azides and alkynes or nitriles, have been applied to macromolecular chemistry, offering molecules ranging from the block copolymers to the complexed macromolecular structures [102].

Sharpless and co-workers have identified a number of reactions that meet the criteria for click chemistry, arguably the most powerful of which discovered to date is the Cu(I)-catalyzed variant of the Huisgen 1,3-dipolar cycloaddition of azides and alkynes to afford 1,2,3-triazoles [103]. Because of Cu(I)-catalyzed variant of the Huisgen 1,3-dipolar cycloaddition of azides and alkynes reactions' quantitative yields, mild reaction condition, and tolerance of a wide range of functional groups, it is very suitable for the synthesis of polymers with various topologies and for polymer modification [104]. Because of these properties of Huisgen 1,3-dipolar cycloaddition, reaction is very practical. Moreover, the formed 1,2,3-triazole is chemically very stable [105].

In recent years, triazole forming reactions have received much attention and new conditions were developed for the 1,3-dipolar cycloaddition reaction between alkynes and azides [106]. 1,2,3-triazole formation is a highly efficient reaction without any significant side products and is currently referred to as a click reaction [107].

Copper(I)-catalyzed reaction sequence which regiospecifically unites azides and terminal acetylenes to give only 1,4-disubstituted 1,2,3 triazoles (equation 2.9).



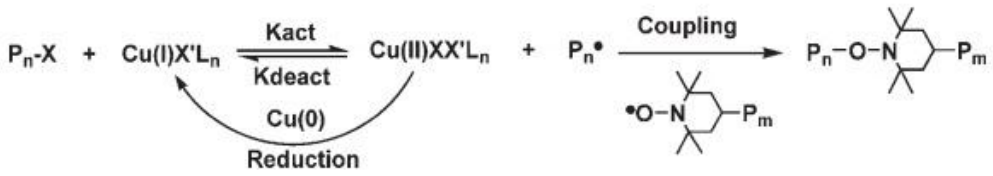
(2.9)

In fact, the discovery of Cu(I) efficiently and regiospecifically unites terminal alkynes and azides, providing 1,4-disubstituted 1,2,3-triazoles under mild conditions,

was of great importance. On the other hand, Fokin and Sharpless proved that only 1,5-disubstituted 1,2,3-triazole was obtained from terminal alkynes when the catalyst switched from Cu(I) to ruthenium(II) [105].

2.2.3 Atom transfer nitroxide radical coupling (ATNRC)

A new reversible coupling strategy termed atom transfer nitroxide radical coupling (ATNRC) [108-115] has the attributes of a "click" reaction. In which the bromine end-functional group of one polymer served as oxidant is reduced to bromine anion and carbon radical is formed. The Cu^{1+} is oxidized to Cu^{2+} in the presence of CuBr/ ligand. Then polymeric radical is immediately captured by another 2,2,6,6-tetramethyl-piperidinyl-1-oxy (TEMPO) end-functional polymer, and alkoxyamine is formed between the two polymers [115] (equation 2.10).In ATNRC reaction, CuBr participated in the reaction was served as reactant and its action was quite different from the ATRP. If some Cu(0) was added, the Cu(0) would react with the formed Cu^{2+} and the Cu^{+} was regenerated, which promoted the reaction completely. Thus, under the ATNRC conditions (such as the Cu(0)/CuBr/PMDETA system), the graft, [110] the star-shaped, [108] and the linear copolymer [111] were prepared successfully with high efficiency.



(2.10)

This reaction involves formation of a carboncentered radical by an atom transfer reaction with Cu(I)Br and trapping of this radical with a persistent nitroxide radical at close to diffusion-controlled rates. The unique aspect of this reaction is its reversibility, in which the product alkoxyamine can readily be converted to the starting incipient radical and parent nitroxide at elevated temperatures (>100 ^{0}C when TEMPO-type nitroxides are used) [116-117]. This methodology has been used to synthesize degradable and reversibly coupled linear multiblock copolymers, block and graft copolymers in the presence of a 10-fold molar excess of copper species per halide end group [114]. The rate determining step in the coupling reaction is the speed (k_{act}) at which the halide end groups on the polymer chains convert (or are

activated) to the carbon-centered radical via atom transfer reactions with Cu(I) species.

2.2 Complex Macromolecular Architecture

The improvement of controlled/living polymerization techniques resulted in definitely management many aspects of complex macromolecular architecture in terms of topology, composition and functionality [119-121]. Anionic polymerization is the most precise and powerful methodology [122], but recent progress in C/LRP additionally has opened the possibility of using many unprotected functional monomers [123, 124].

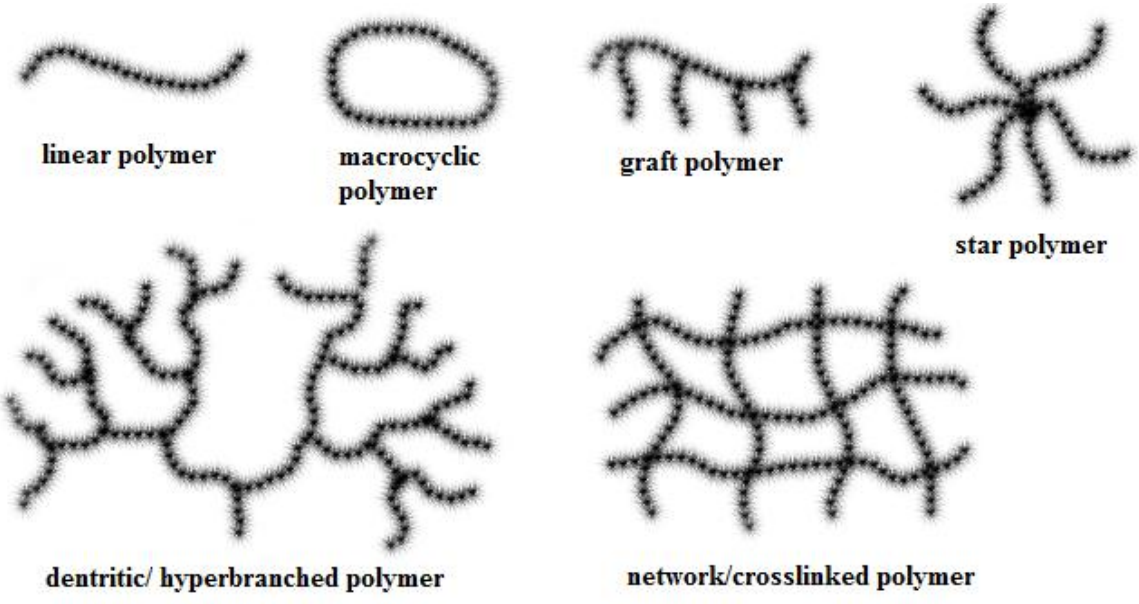


Figure 2.1: Illustration of polymers with various topologies.

The various C/LRP techniques allow the synthesis of well-defined polymeric materials with different topology, including linear, star, cyclic, brush, branched polymers, and cross-linked networks (gels) (Figure 2.1).

2.3.1 Cyclic polymers

Before the concept of macromolecules concept was established, most chemists believed that polymers consisted of aggregation of cyclic polymers. After the concept was established, macromolecules became commonly represented as long, flexible random coiled chains, with the possibility of some cyclic structures, though

in small amounts [125]. Now various kinds of polymer structures have been architected by developing synthetic methods as depicted in figure 2.2.

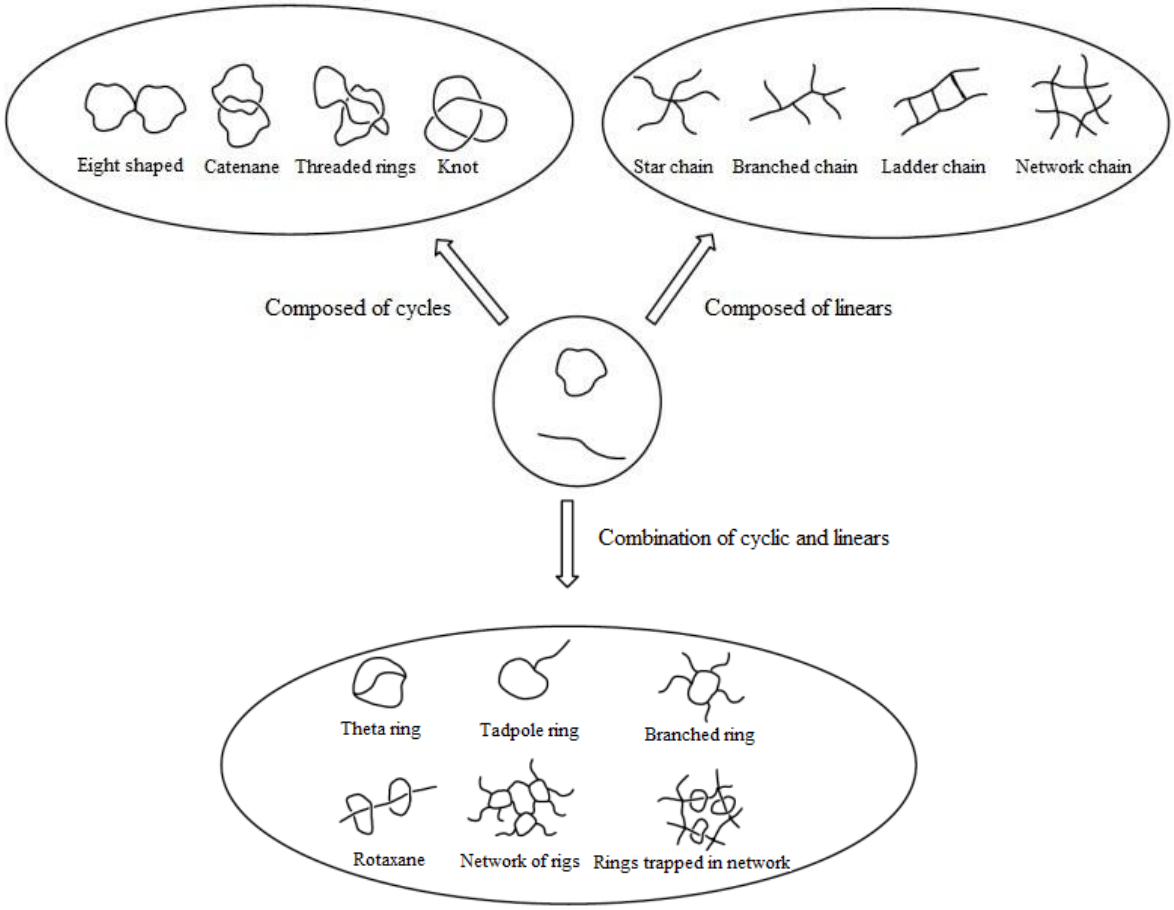


Figure 2.2: Possible structures of linear chains and cycles.

2.3.1.1 Classification of cyclization process

Although some interesting synthetic processes of cyclic polymers have been addressed, the cyclization principle can be classified into two main methods as indicated in figure 2.3. One is the utilization of the ring-chain equilibrium that occurs in many polycondensation and ring opening polymerization. Another is the end-to-end cyclization method that can be used for synthesizing cyclic polymers from α,ω–difunctional linear precursors. The ring-closure reaction by the end-to-end cyclization is further divided into intermolecular reaction and intramolecular reaction, i.e., bimolecular process and unimolecular process, respectively [125].

1) Ring-chain equilibrium method (Backbiting method, Ring expansion polymerizat)

2) End-to-end cyclization method

   a) Bimolecular process by α,α'-difunctional polymer

(X, Y: complementarily reactive groups)

   b) Unimolecular process by α,ω-heterodifunctional polymer

(X, Y: complementarily reactive groups)

Figure 2.3: Polymer cyclization processes.

2.3.1.1.1 Ring-chain equilibrium method

It is usually difficult to synthesize cyclic polymers by taking the random chain walk into consideration, but the formation of cyclic polymers is known to occur simultaneously with chain growth in many step-growth processes and even in addition polymerizations. A theory that accounts for the competition between linear growth and cyclization was proposed by Jacobson and Stockmayer. This theory has been shown to apply to ring-opening polymerization and step growth, which implies the presence of functional links along the polymer backbone. The ring content is enhanced upon dilution and the formation of small ring size is favored. The synthesis of such cyclic polymers has been reported since the 1950s in the preparation of polyesters and polyamides. Cyclic polymers that result from ring-chain equilibriums

cover a broad range of molecular weights, because they mainly are formed by backbiting reactions. However, in the early days, experimental confirmation was much too difficult because the synthetic methods were not well developed. Today, the development of many analytical instruments allows separation of cyclic and linear constituents, and the ring-chain equilibrium has been utilized [125].

2.3.1.1.2 End-to-end cyclization method

End-to-end cyclization methods can be divided into bimolecular and unimolecular processes. One consists of bimolecular cyclization between a living α,ω-dicarbanionic polymer and a difunctional electrophile compound under extreme dilution conditions.

The controlled molecular weight can be synthesized by the end-to-end ring closure method. Reaction of a linear α,ω-difunctional chain results in a certain amount of cyclic polymers of the same degree of polymerization as that of a linear precursor. It follows that the lower the concentration of the cyclization medium was used, the higher the resulting cyclic polymer content was obtained. There is no theoretical limit as to the cyclic polymers that can be formed by this method.

A bimolecular process was reported by two independent groups, i.e., Höcker and Rempp in 1980. Macrocyclic polymers have been successfully prepared by the coupling reaction of a two-ended living polystyryl anion with a difunctional electrophile such as α,α'-dibromo-*p*-xylene under high dilution to yield cyclic and linear mixtures. The cyclic polymer was isolated by a fractional precipitation. This bimolecular end-to-end reaction process has been used for synthesizing cyclic polystyrene by many researchers.

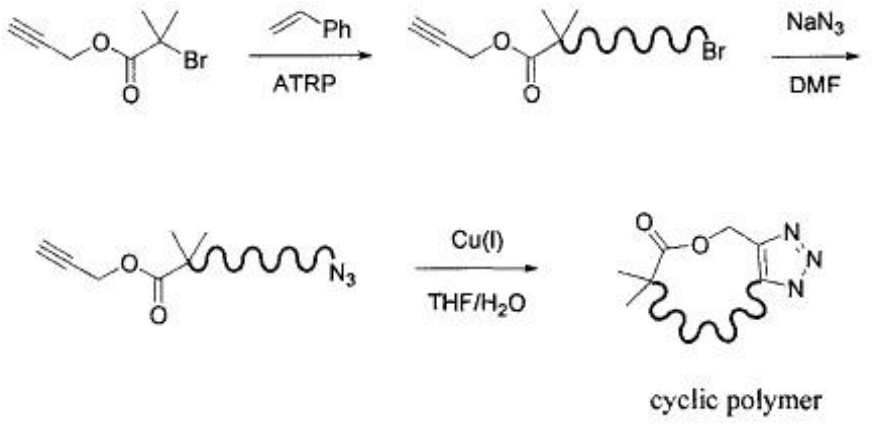
Another strategy for cyclic polymers is an intramolecular (unimolecular) cyclization of linear α,ω-heterodifunctional polymers, which is proposed by Deffieux. In this case, the heterodifunctional polymers were used as precursors of the cyclic polymers, and α,ω-difunctional polymers should be designed before the cyclization . The yields of the cyclic polymers were reported to be high (up to 90%) [125].

2.3.1.2 Synthesis of cyclic polymers

The synthesis of cyclic polymers has long been a goal chemists. The unique topology of cyclic polymers leads to different physical properties when compared to linear

polymers. For example, cyclic polymers typically have different viscosities, glass transition temperatures, and densities than linear polymers of the same molecular weight and composition [126]. Cyclic and linear polymers also occupy different volumes. If a cyclic polymer is cleaved at a single bond, it will result in a linear polymer of a similar molecular weight, but a larger hydrodynamic diameter. This result has important consequences when analyzing cyclic polymer, because GPC actually measures the hydrodynamic diameter of a polymer than its true molecular weight.

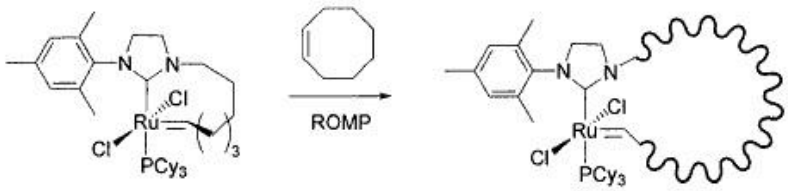
Despite much effort, the formation of cyclic polymers has remained challenging. Most attempts to form cyclic polymers involve the post-polymer cyclization of a linear precursor. This method requires very dilute conditions in order to ensure an intramolecular cyclization reaction rather than an intermolecular condensation. As a result, this procedure is often low-yielding, resulting in a mixture of linear and cyclic polymers that are difficult to separate. A recent and promising example of such a post-polymer cyclization is shown in (equation 2.11) [126]. Alkyne- functionalized polystyrene was formed using ATRP, and the terminal bromine was converted into an azide. The cyclization reaction made use of the extremely high-yielding ‘‘click’’ reaction between an azide and a terminal alkyne to form a triazole. Although this reaction was efficient at forming macrocycles, it has only been used on short polymers (lee than 4200 Da).



(2.11)

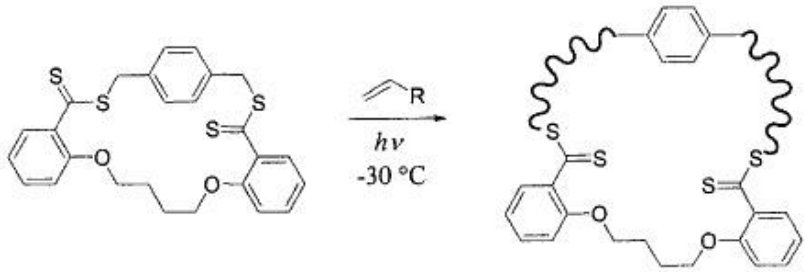
The direct synthesis of cyclic from cyclic initiators would be a more efficient route, because it would eliminate the difficulty of separating cyclic from linear polymers. However, this technique requires a well-designed initiator, and few example exist in the literature. Of particular note is the development of a cyclic ruthenium catalyst for

ring-opening metathesis polymerization (ROMP) developed by Grubbs and coworkers (equation 2.12) [126]. This initiator has been used successfully in ROMP to from cyclic polymers from a variety monomers, including cyclooctene and 1,5-cycloctadiene.



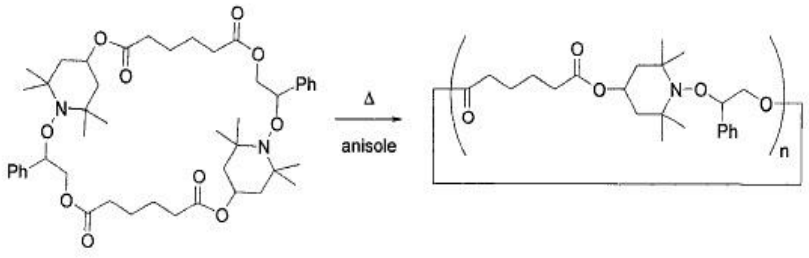
(2.12)

Pan and coworkers have used a cyclic bis-dithioester initiator in reversible addition fragmentation transfer (RAFT) to form cyclic polymers (equation 2.13) [126]. They used γ-ray irradiation at -30 ^{o}C to homolytically cleave the cyclic initiator at either of its C-S bonds, forming a stable sulfur radical and an unstable benzyl radical. The benzyl radical initiates the polymerization, and the polymer chain propagation, and combination occur repeatedly to form a cyclic polymer with a controlled ring size and a low polydispersity index.



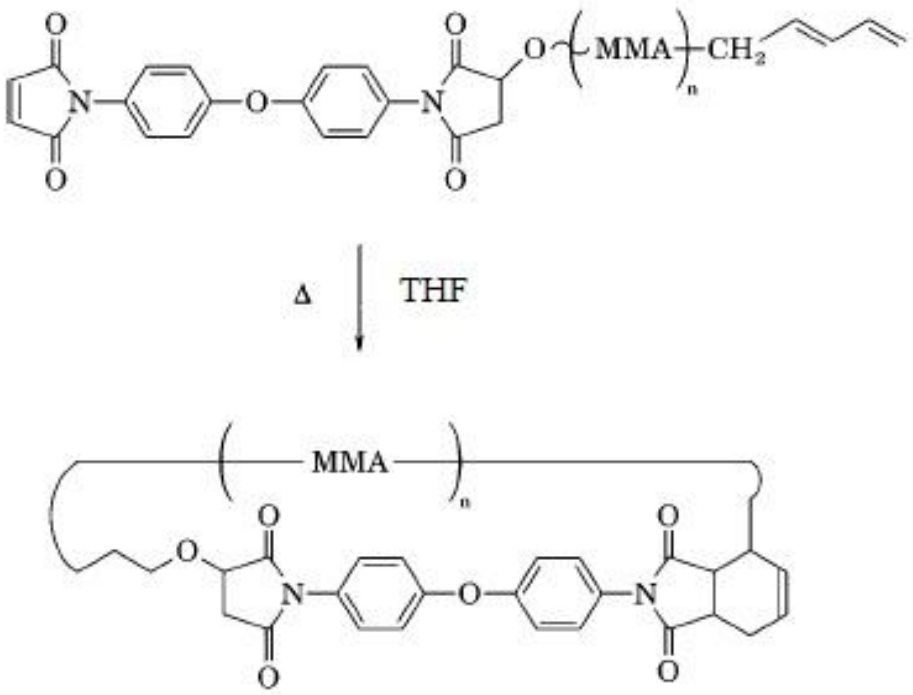
(2.13)

Yamaguchi et al. have made alkoxyamine-containing macrocyles using a reversible radical crossover reaction between nitroxide (equation 2.14), but they not used these cyclic alkoxyamines in NMP [126].



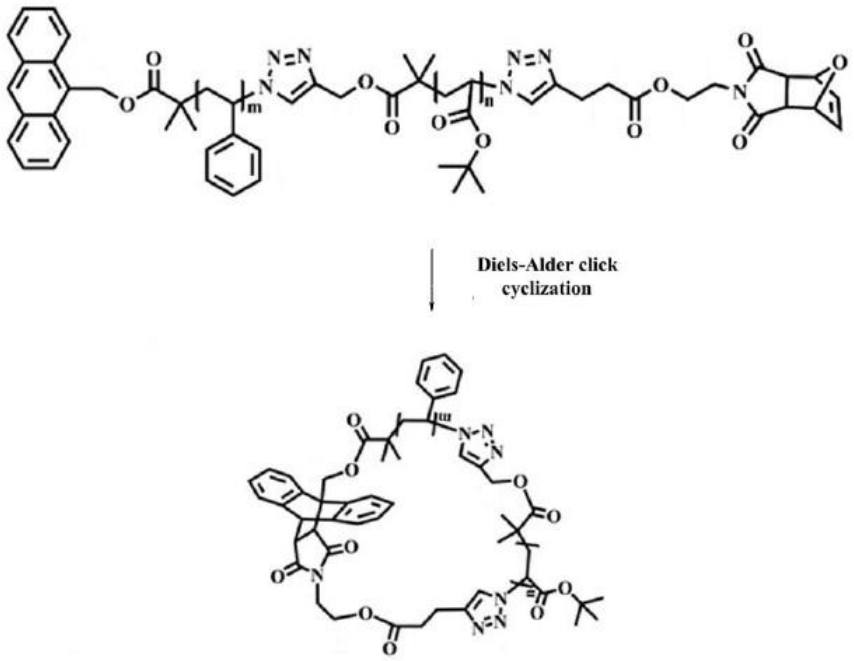
(2.14)

Mizawa et al first reported an intramolecular Diels-Alder macromolecular cyclization between maleimide and pentadienyl end groups of poly(methyl methacrylate) (PMMA) in dilute tetrahydrofuran at reflux temperature yielding a cyclic PMMA (*c*-PMMA) in a good yield (equation 2.15) [18].



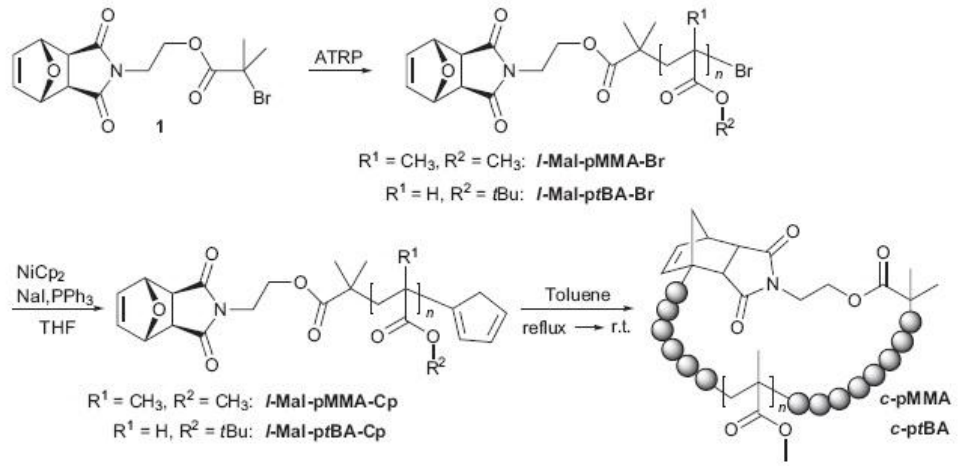
(2.15)

More recently, Diels-Alder macromolecular cyclization of polymeric precursors with anthracene and maleimide terminal groups was reported by Durmaz et al [32]. Well - defined linear heterotelechelic homo and block copolymer precursors, e.g. polystyrene (PS), PS-*b*-poly(*tert*-butyl acrylate) (P*t*BA) (equation 2.16), and PS-*b*-poly(ε-caprolactone) (PCL), containing anthracene and furan protected maleimide end-groups were prepared using the CuAAC click reaction between an α-anthracene-PS-ω-azide and an α-alkyne-ω-maleimide containing precursor or the corresponding α-alkyne-ω-maleimide polymers. The resulting polymeric precursors were subsequently clicked to yield corresponding cyclic homo (*c*-PS) and block copolymers, *c*-(PS-*b*-P*t*BA) and *c*-(PS-*b*-PCL), via an intramolecular Diels-Alder reaction at reflux temperature of toluene for 48 h under dilute concentrations (7-4 X 10^{-5} M).



(2.16)

Shortly thereafter Kowollik group reported the Diels-Alder macromolecular cyclization depending on maleimide and cyclopentadiene functional groups [39]. The linear furan protected α-maleimide-ω-cyclopentadienyl terminated polymer precursors were efficiently clicked via intramolecular Diels-Alder reaction at high dilution under relatively mild conditions yielding *c*-PMMA and *c*-P*t*BA (equation 2.17),



(2.17)

2.3.2 Tadpole shaped polymers

The tadpole shaped polymer, which consists of a cyclic polymer as head and a linear polymer as tail.

There are three general synthetic strategies. a) Cyclization of linear polymers with two complementary reactive functions sited at the end and the middle of chain, respectively, under dilute condition; b) couple reaction of one reactive group in cyclic polymer with one terminal function of linear polymer; c) couple reaction of two reactive anions (or cations) at both end of the chain with two reactive cations (or anions) at one end of the linear polymer chain [40].

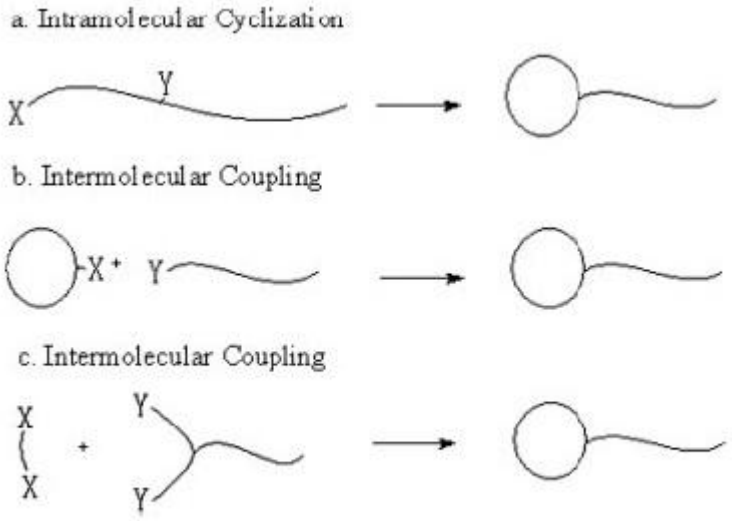


Figure 2.4: Synthesis of tadpole-shaped polymer

3. EXPERIMENTAL WORK

3.1 Materials

Styrene (St, 99%, Aldrich) was passed twice through basic alumina column to remove inhibitor and then distilled over CaH_2 in vacuum prior to use. ε-Caprolactone (ε-CL, 99%, Aldrich) was distilled over CaH_2 in vacuum. *N,N,N',N'',N''*-pentamethyldiethylenetriamine (PMDETA, Aldrich) was distilled over NaOH prior to use. Poly(ethylene glycol monomethyl ether) (Me-PEG-OH) (M_n = 550 g/mol, Acros) was dried over anhydrous toluene by azeotropic distillation. 9-Anthracene methanol (97%, Aldrich), *N,N'*-dicyclohexylcarbodiimide (DCC, 99%, Aldrich), 4-dimethylaminopyridine (DMAP, 99%, Acros), and CuBr (99.9%, Aldrich) were used as received. Dichloromethane (CH_2Cl_2) was purchased from Aldrich and used after distillation over P_2O_5. Tetrahydrofuran (THF; 99.8%, J.T. Baker) was dried and distilled over benzophenone-Na. Solvents unless specified here were purified by conventional procedures. All other reagents were purchased from Aldrich and used as received without further purification.

3.2 Instrumentation

The ^1H NMR (250 MHz) spectra were recorded on a Bruker NMR Spectrometer in $CDCl_3$. The conventional gel permeation chromatography (GPC) measurements were carried out with an Agilent instrument (Model 1100) consisting of a pump, refractive index (RI), and ultraviolet (UV) detectors and four Waters Styragel columns (guard, HR 5E, HR 4E, HR 3, HR 2), (4.6 mm internal diameter, 300 mm length, packed with 5 μm particles). The effective molecular weight ranges are 2000-4,000,000, 50-100,000, 500-30,000, and 500–20,000, respectively. THF and toluene were used as eluent at a flow rate of 0.3 mL/min at 30 °C and as internal standard, respectively. The apparent molecular weights ($M_{n,GPC}$ and $M_{w,GPC}$) and polydispersities (M_w/M_n) were determined with a calibration based on linear PS standards using PL Caliber Software from Polymer Laboratories. The second GPC set-up (TD-GPC) with an Agilent 1200 model isocratic pump, four Waters Styragel columns (guard, HR 5E,

HR 4, HR 3, and HR 2), and a Viscotek TDA 302 triple detector including refractive index (RI), dual laser light scattering (DLLS) (λ = 670 nm, 90° and 7°) and a differential pressure viscometer was conducted to measure the absolute molecular weights ($M_{n,TDGPC}$ and $M_{w,TDGPC}$) in THF with a flow rate of 0.5 mL/min at 35 ^{o}C. Three detectors were calibrated with a PS standard with narrow molecular weight distribution (M_n = 115,000 g/mol, M_w/M_n = 1.02, [η] = 0.519 dL/g at 35°C in THF, dn/dc = 0.185 mL/g) provided by Viscotek company. UV spectra were recorded on a Shimadzu UV-1601 spectrophotometer in CH_2Cl_2.

3.3 Synthesis Methods

Anthracen-9-ylmethyl 2,2,5-trimethyl-1,3-dioxane-5-carboxylate, **2**, [127] anthracen-9-ylmethyl 3-hydroxy-2-(hydroxymethyl)-2-methylpropanoate, **3**, [127] α-furan-protected-maleimide-ω-alkyne linkage, **5**, [128] were prepared according to our published procedures.

3.3.1 Synthesis of 2,2,5-trimethyl-[1,3]dioxane-5-carboxylic acid (1)

The 2,2-bis(hydroxymethyl)propanoic acid (8 g, 59.6 mmol) along with *p*-TSA (0.45 g, 2.32 mmol), and 2,2-dimethoxypropane (11.2 mL, 89.4 mmol) dissolved in 40 mL of dry acetone, and stirred 2h at room temperature. In the vicinity of 2h, while stirring continued the reaction mixture was neutralized with 6 mL of totally NH_4OH (25%), and absolute ethanol (1:5), filtered off by-products and subsequent dilution with dichloromethane (100 mL), and once extracted with distilled water (40 mL). The organic phase dried with Na_2SO_4, concantrated to yield 7.4 g (71%) as white solid after evaporation of the solvent. ^{1}H NMR ($CDCl_3$, δ) 4.18 (d, 2H, CC*H*$_2$O), 3.63 (d, 2H, CC*H*$_2$O), 1.38 (s, 3H, C*CH*$_3$) 1.36 (s, 3H, C*CH*$_3$), 1.18 (s, 3H, C=OC(CH_2O)$_2$*CH*$_3$).

3.3.2 Synthesis of anthracen-9ylmethyl 2,2,5-trimethyl-[1,3]dioxane-5-carboxylate (2)

9-Anthracene methanol (2 g, 9.6 mmol) was dissolved in 50 mL of CH_2Cl_2 and **1** (2 g, 11.5 mmol), and DMAP (1.17 g, 9.6 mmol) were added to the reaction mixture in that order. After stirring 5 minutes at room temperature, DCC (2.37 g, 11.5 mmol) dissolved in 20 mL of CH_2Cl_2 was added. Reaction mixture was stirred overnight at

room temperature and urea byproduct was filtered. Then reaction mixture was extracted with water/ CH_2Cl_2 (1:4) two times and combined organic phase was dried with Na_2SO_4. Solvent was evaporated and the remaining product was purified by column chromatography over silica gel eluting with hexane/ethyl acetate (4:1) to give pale yellow oil (Yield = 2.97 g; 85 %). ^{1}H NMR ($CDCl_3$, δ) 8.50 (s, 1H, Ar*H* of anthracene), 8.32 (d, 2H, Ar*H* of anthracene), 8.02 (d, 2H, Ar*H* of anthracene), 7.60-7.45 (m, 4H, Ar*H* of anthracene), 6.2 (s, 2H, *CH*$_2$-anthracene), 4.14 (d, 2H, CC*H*$_2$O), 3.58 (d, 2H, CC*H*$_2$O), 1.38 (s, 3H, C*CH*$_3$), 1.35 (s, 3H, C*CH*$_3$), 1.08 (s, 3H, C=OC(CH_2O)$_2$*CH*$_3$).

3.3.3 Synthesis of anthracen-9ylmethyl 3-hydroxy-2-(hydroxymethyl)-2-methylpropanoate (3)

9-anthrylmethyl 2,2,5-trimethyl-1,3-dioxane-5-carboxylate (2.95 g, 8.1 mmol) was dissolved in a mixture of 20 mL of THF and 10 mL of 1 M HCl. The reaction mixture was stirred for 2 h at room temperature. The precipitated product was filtered off and reaction mixture was concentrated and extracted with 160 mL of CH_2Cl_2 and 40 mL of water. The combined organic phase was dried with Na_2SO_4 and concentrated. Hexane was added to the reaction mixture and it was kept in deep freeze overnight to give white solid (Yield = 2.4 g, 91 %). ^{1}H NMR ($CDCl_3$, δ) 8.52 (s, 1H, Ar*H* of anthracene), 8.30 (d, 2H, Ar*H* of anthracene), 8.03 (d, 2H, Ar*H* of anthracene), 7.60-7.45 (m, 4H, Ar*H* of anthracene), 6.2 (s, 2H, *CH*$_2$-anthracene), 3.85 (d, 2H, C*H*$_2$OH), 3.66 (d, 2H, C*H*$_2$OH), 2.17(br, 2H, OH), 1.01 (s, 3H, C*CH*$_3$).

3.3.4 Synthesis of anthracen-9-ylmethyl 3-(2-bromo-2-methylpropanoyloxy)-2-(hydroxymethyl)-2-methylpropanoate (4)

3 (2.0 g, 6.2 mmol, 1.1 equiv) was dissolved in 20 mL of CH_2Cl_2 in a 100 mL of round- bottom flask, and triethylamine (1.28 mL, 9.26 mmol, 1.5 equiv) was added to the solution and the mixture was cooled to 0 °C. 2-Bromoisobutryl bromide (0.69 mL, 5.6 mmol, 1 equiv.) in 10 mL of CH_2Cl_2 was added dropwise to the solution within 30 min. under nitrogen. The mixture was further stirred at 0 °C for 1 h, then warmed to room temperature and stirred overnight. After filtration the mixture was extracted with water, diluted HCl (100 mL) and subsequently saturated $NaHCO_3$ solution (100 mL). The aqueous layers were again extracted with CH_2Cl_2, and combined organic layers were dried over Na_2SO_4. The solution was concentrated,

and the crude product was purified by column chromatography over silica gel eluting with hexane/ethyl acetate (3:1) gradually increased to (1:1) to give **4** as a yellow viscous oil, which solidified upon sitting in the refrigerator (Yield = 1.6 g, 60%). ^{1}H NMR (250 MHz, $CDCl_3$, δ) 8.5 (s, 1H, Ar*H* of anthracene), 8.3 (d, 2H, Ar*H* of anthracene), 8.0 (d, 2H, Ar*H* of anthracene), 7.7-7.4 (m, 4H, Ar*H* of anthracene), 6.2 (s, 2H, CH_2-anthracene), 4.3 (dd, 2H, CH_2OC=O), 3.7 (t, 2H, CH_2OH), 2.3 (br, 1H, CH_2O*H*), 1.7 (d, 6H, CBr(CH_3)$_2$), 1.2 (s, 3H, CCH_3).

3.3.5 Synthesis of linear anthracene-, OH- and azide-terminated PS (*l*-α-anthracene-OH-ω-azide-PS)

St (10 mL, 87 mmol), PMDETA (0.18 mL, 0.87 mmol), CuBr (0.124 g, 0.87 mmol) and **4** (0.41 g, 0.87 mmol) were added in a Schlenk tube in that order and the reaction mixture was degassed by three freeze-pump-thaw (FPT) cycles and left in vacuum. The tube was then placed in a thermostated oil bath at 110 °C for 25 min. After that time, the dark green polymerization mixture was diluted with THF, passed through a neutral alumina column to remove the catalyst, and precipitated in methanol. The polymer was dried overnight in a vacuum oven at 40 °C ($[M]_0/[I]_0$=100; $[I]_0$:$[CuBr]_0$:$[PMDETA]_0$ = 1:1:1; conv. = 22%; $M_{n,theo}$ = 2800 g/mol, $M_{n,NMR}$ = (33 (DP_n) X 104 g/mol + 473 g/mol (MW of **4**) = 3900 g/mol), $M_{n,GPC}$ = 3700 g/mol, M_w/M_n =1.18, relative to PS). ^{1}H NMR (250 MHz, $CDCl_3$, δ) 8.5 (br, 1H, Ar*H* of anthracene), 8.3 (br, 2H, Ar*H* of anthracene), 8.0 (br, 2H, Ar*H* of anthracene), 7.6-7.4 (m, 4H, Ar*H* of anthracene), 7.3-6.2 (Ar*H* of PS), 6.1 (s, 2H, CH_2-anthracene), 4.4 (br, 1H, C*H*(Ph)Br, end group of PS), 3.7 (s, 2H, CH_2OH), 3.6-3.4 (br, 2H, CH_2OC=OC(CH_3)$_2$-PS), 2.2-0.6 (aliphatic protons of PS, CCH_3 and CH_2OC=O-C(CH_3)$_2$-PS).

Next, *l*-α-anthracene-OH-ω-bromide-PS (1.85 g, 0.50 mmol, $M_{n,GPC}$ = 3700 g/mol, 1 equiv.) was dissolved in DMF (15 mL), and NaN_3 (0.65 g, 10.0 mmol, 20 equiv.) was added to the reaction mixture. After stirring overnight at room temperature, the solution was precipitated in excess amount of methanol and recovered polymer was dissolved in THF and precipitated in methanol. This dissolution-precipitation procedure was repeated two times. The obtained polymer was dried overnight in a vacuum oven at 40 °C (Yield = 1.8 g, 97%; $M_{n,GPC}$ = 3850 g/mol, M_w/M_n = 1.15, relative to PS standards). ^{1}H NMR (250 MHz, $CDCl_3$, δ) 8.5 (br, 1H, Ar*H* of

anthracene), 8.3 (br, 2H, Ar*H* of anthracene), 8.0 (br, 2H, Ar*H* of anthracene), 7.6-7.4 (m, 4H, Ar*H* of anthracene), 7.3-6.2 (ArH of PS), 6.1 (s, 2H, CH_2-anthracene), 3.9 (br, 1H, C*H*(Ph)N_3, end group of PS), 3.7 (s, 2H, CH_2OH), 3.6-3.4 (br ,2H, CH_2OC=OC$(CH_3)_2$-PS), 2.2-0.6 (aliphatic protons of PS, CCH_3 and CH_2OC=O-C(C$H_3)_2$-PS).

3.3.6 Synthesis of oxanorbornenyl alkyne (5)

Maleic anhydride (60.0 g, 0.6 mol) was suspended in 150 mL of toluene and the mixture warmed to 80 °C. Furan (66.8 mL, 0.9 mol) was added via syringe and the turbid solution was stirred for 6 h. The mixture was then cooled to ambient temperature white solids formed during standing were collected by filtration and washed with 2 × 30 mL of petroleum ether and once with diethyl ether (50 mL) afforded 4,10-dioxatricyclo[5.2.1.$0^{2,6}$]dec-8-ene-3,5-dione **(5.a)** as white needless. Yield: 80.2 g (80%). ^{1}H NMR ($CDCl_3$, δ) 6.57 (s, 2H, C*H*=C*H*, bridge protons), 5.45 (s, 2H, -C*H*O, bridge-head protons), 3.17 (s, 2H, C*H*-C*H*, bridge protons).

Next, **5.a** (10.0 g, 60.0 mmol) was suspended in methanol (150 mL) and the mixture cooled to 0 °C. A solution of ethanolamine (3.6 mL, 60 mmol) in 30 mL of methanol was added dropwise (10 min) to the reaction mixture, and the resulting solution was stirred for 5 min at 0 °C, then 30 min at ambient temperature, and finally refluxed for 6 h. After cooling the mixture to ambient temperature, solvent was removed under reduced pressure, and residue was dissolved in 150 mL of CH_2Cl_2 and washed with 3 × 100 mL of water. The organic layer was separated, dried over Na_2SO_4 and filtered. Removal of the solvent under reduced pressure gave white-off solid which was further purified by flash chromatography eluting with ethylacetate (EtOAc) to give 4-(2-hydroxyethyl)-10-oxa-4-azatricyclo[5.2.1.$0^{2,6}$]dec-8-ene-3,5-dione **(5.b)** as a white solid. Yield: 4.9 g (40%). ^{1}H NMR ($CDCl_3$, δ) 6.51 (s, 2H, C*H*=C*H*, bridge protons), 5.26 (s, 2H, -C*H*O, bridge-head protons), 3.74-3.68 (m, 4H, NCH_2CH_2OH), 2.88 (s, 2H, C*H*-C*H*, bridge protons).

Finally, 4-Pentynoic acid (1.12 g, 11.5 mmol, 1.2 equiv), DMAP (0.58 g, 4.78 mmol, 0.5 equiv) and **5.b** (2.00 g, 9.56 mmol, 1 equiv) were dissolved in 40 mL of dry CH_2Cl_2. After stirring 5 min at room temperature, DCC (2.40 g, 11.5 mmol, 1.5 equiv) dissolved in 15 mL of CH_2Cl_2 was added to the reaction mixture. The reaction mixture was stirred overnight at room temperature. After filtration, the solvent was

removed, and the remaining product was extracted with CH_2Cl_2/water. The aqueous phase was again extracted with CH_2Cl_2, and the combined organic phases were dried with Na_2SO_4, and concentrated to dryness. The crude product was purified by column chromatography over silica gel eluting with ethyl acetate/hexane (1:1) to give **5** as a white solid (yield: 2.6 g; 94%). ^{1}H NMR ($CDCl_3$, δ) 6.5 (s, 2H, vinyl protons), 5.2 (s, 2H, C*H*CH=CHC*H*, bridge-head protons), 4.2 (t, 2H, $NCH_2CH_2OC=O$), 3.7 (t, 2H, $NCH_2CH_2OC=O$), 2.8 (s, 2H, C*H*-C*H*, bridge protons), 2.5 (bs, 4H, $C=OCH_2CH_2C\equiv CH$), 1.9 (s, 1H, $C=OCH_2CH_2C\equiv CH$).

3.3.7 Synthesis of linear anthracene-, OH- and maleimide-terminated PS (*l*-α-anthracene- OH-ω-maleimide-PS)

The *l*-α-anthracene-OH-ω-azide-PS (1.7 g, 0. 44 mmol, $M_{n,GPC}$ = 3850 g/mol, 1 equiv) was dissolved in DMF (10 mL), and **5** (0.382 g, 1.32 mmol, 3 equiv), PMDETA (0.092 mL, 0.44 mmol, 1 equiv), and CuBr (0.063 g, 0.44 mmol, 1 equiv) were added in a 25 mL of Schlenk tube in that order. The reaction mixture was degassed by three FPT cycles, left in vacuum and stirred at room temperature overnight. After that time, the solution was diluted with THF and filtered through a column filled with neutral alumina to remove copper complex and finally precipitated in methanol. This dissolution-precipitation procedure was repeated two times. The obtained polymer was dried overnight in a vacuum oven at 40 °C (Yield = 1.65 g, 90%; $M_{n,GPC}$ = 4200 g/mol, M_w/M_n = 1.13, relative to PS standards). ^{1}H NMR ($CDCl_3$, δ) 8.5 (br, 1H, Ar*H* of anthracene), 8.3 (br, 2H, Ar*H* of anthracene), 8.0 (s, 2H, Ar*H* of anthracene), 7.5 (s, 4H, Ar*H* of anthracene), 7.3-6.2 (Ar*H* of PS), 6.1 (s, 2H, CH_2-anthracene), 5.2 (br, 2H, C*H*CH=CHC*H*, bridge-head protons), 5.1 (br, 1H, C*H*(Ph)-triazole, end group of PS), 4.2 (br, 2H, $NCH_2CH_2OC=O$), 3.7 (br, 4H, $NCH_2CH_2OC=O$ and CH_2OH), 3.6-3.4 (br ,2H, $CH_2OC=OC(CH_3)_2$-PS), 2.8 (br, 4H, triazole-$CH_2CH_2C=O$ and $CH_2NC=OCH$-C*H*, bridge protons), 2.6 (br, 2H, triazole-$CH_2CH_2C=O$), 2.0-0.6 (aliphatic protons of PS, CCH_3 and $CH_2OC=O$-$C(CH_3)_2$-PS).

3.3.8 Preparation of cyclic-PS with an hydroxyl group ((*c*-PS)-OH) via diels-alder click reaction of *l*-α-anthracene-OH-ω-maleimide-PS

l-α-Anthracene-OH-ω-maleimide-PS (0.50 g, 0.12 mmol, $M_{n,GPC}$ = 4200 g/mol) was dissolved in toluene (400 mL). The solution was bubbled with nitrogen for 30 min

and refluxed for 48 h under nitrogen in the dark. After that time, solvent was removed under high vacuum, and residual solid was dissolved in THF, and subsequently precipitated in methanol. The polymer was dissolved in THF and precipitated in methanol/diethyl ether (2:1, v:v). The solution was separated from the solid via decantation and concentrated under high vacuum. The residual solid was finally dissolved in THF and precipitated in methanol. The obtained polymer was dried overnight in a vacuum oven at 40 °C (Yield = 0.3 g, 60%; $M_{n,GPC}$ = 3400 g/mol, M_w/M_n = 1.11, relative to linear PS). ^{1}H NMR (250 MHz, $CDCl_3$, δ) 7.4-6.2 (Ar*H* of PS), 5.4 (br, 2H, OC*H*$_2$-Diels-Alder adduct), 5.1 (br, 1H C*H*(Ph)-triazole), 4.8 (br, 1H, C*H*, bridge-head proton), 3.9-3.1 (br, 10H, NC*H*$_2$CH$_2$OC=O, NCH$_2$C*H*$_2$OC=O, C*H*$_2$OH, C*H*-C*H*, bridge protons and C*H*$_2$OC=OC(CH$_3$)$_2$-PS), 2.9 (br, 2H, triazole-C*H*$_2$CH$_2$C=O), 2.5 (br, 2H, triazole-CH$_2$C*H*$_2$C=O), 2.0-0.8 (aliphatic protons of PS, CC*H*$_3$ and CH$_2$OC=O-C(C*H*$_3$)$_2$-PS).

3.3.9 Synthesis of (*c*-PS)-Br via esterification between (*c*-PS)-OH and 2-bromoisobutryl bromide

(*c*-PS)-OH (0.28 g, 0.067 mmol, $M_{n,GPC,linear}$ = 4200 g/mol, 1 equiv) was dissolved in 10 mL of CH_2Cl_2 in a 50 mL of round- bottom flask. Subsequently, triethyl amine (0.18 mL, 1.33 mmol, 20 equiv) was added to the solution and the mixture was cooled to 0 °C. 2-Bromoisobutryl bromide (0.082 mL, 0.67 mmol, 10 equiv) in 2 mL of CH_2Cl_2 was added dropwise to the solution within 10 min. under nitrogen. The mixture was further stirred at 0 °C for 30 min. and then warmed to room temperature and stirred overnight. After that time, the solution was evaporated to half of its volume and precipitated in 50 mL of methanol. The dissolution (CH_2Cl_2)-precipitation (methanol) procedure was repeated two times for purification of the polymer. The final product was dried overnight in a vacuum oven at 40 °C (Yield = 0.25 g, 86%; $M_{n,theo}$ = 4350 g/mol (a sum of $M_{n,GPC,linear}$ = 4200 g/mol + 150 g/mol), $M_{n,GPC}$ = 3500 g/mol, M_w/M_n =1.11, relative to linear PS). ^{1}H NMR (250 MHz, $CDCl_3$, δ) 7.4-6.2 (Ar*H* of PS), 5.4 (br, 2H, OC*H*$_2$-Diels-Alder adduct), 5.1 (br, 1H C*H*(Ph)-triazole), 4.7 (br, 1H, C*H*, bridge-head proton), 4.2 (br, 2H, C*H*$_2$OC=OC(CH$_3$)$_2$-Br), 3.7-3.1 (br, 8H, NC*H*$_2$CH$_2$OC=O, NCH$_2$C*H*$_2$OC=O, C*H*-C*H*, bridge protons and C*H*$_2$OC=OC(CH$_3$)$_2$-PS), 2.8 (br, 2H, triazole-C*H*$_2$CH$_2$C=O), 2.5 (br, 2H, triazole-CH$_2$C*H*$_2$C=O), 2.0-0.8 (aliphatic protons of PS, CC*H*$_3$ and CH$_2$OC=O-C(C*H*$_3$)$_2$-PS).

3.3.10 Synthesis of TEMPO terminated-PEG (PEG-TEMPO)

PEG-OH (5 g, 8 mmol, M_n = 550) was dissolved in 150 mL of CH_2Cl_2. Succinic anhydride (3.13 g, 32.0 mmol), triethylamine (Et_3N) (5.6 mL, 40 mmol) and DMAP (1.46 g, 12.0 mmol) were added to the reaction mixture. After stirring overnight at room temperature, solution was poured into ice-cold water (150 mL) and extracted with CH_2Cl_2. The organic layer was washed with 1 M HCl (150 mL) and then with distilled water. Finally, organic phase was dried with anhydrous Na_2SO_4 and the solvent was removed in vacuum to give mono carboxylic acid end-functionalized PEG (PEG-COOH) as colorless oil (Yield = 5 g, 95%; $M_{n,theo}$ = 650, $M_{n,NMR}$ =615, $M_{n,GPC}$ =450, M_w/M_n =1.1, relative to PS standards). ^{1}H NMR ($CDCl_3$, δ) 4.2 (d, 4H, C=OOCH_2), 3.65-3.5 (m, -OCH_2CH_2O-, PEG backbone), 3.35 (s, 3H, OCH_3), 2.6 (bs, 4H, C=OCH_2CH_2C=O).

NEXT, PEG-COOH (1.00 g, 1.53 mmol, based on $M_{n,theo}$ = 650) was dissolved in 20 mL of dry CH_2Cl_2. 4-Hydroxy-TEMPO (0.79 g, 4.61 mmol) and DMAP (0.186 g, 1.n53 mmol) were added to the reaction mixture in that order. After stirring for 5 minutes at room temperature, DCC (0.95 g, 4.61 mmol) in 10 mL of CH_2Cl_2 was added to solution. The reaction was continued via stirring for 24 h at room temperature. Reaction solution was concentrated under reduced pressure. The crude product was purified by column chromatography over silica gel eluting first with CH_2Cl_2/ethyl acetate (1/1), then CH_2Cl_2/CH_3OH (10/1) in order to give red oil (Yield = 1.05 g, 85 %; $M_{n,theo}$ = 800; $M_{n,GPC}$ = 650; M_w/M_n = 1.06, relative to PS standards) DPn= 13.

3.4.11 Synthesis of TEMPO terminated-PCL (PCL-TEMPO)

The PCL-TEMPO was prepared by ROP of ε-CL (5.0 mL, 0.047 mol) in bulk using tin(II)-2-ethylhexanoate (0.01 mL, 0.03 mmol) as catalyst and 4-hydroxy-TEMPO (0.270 g, 1.57 mmol) as initiator at 110 °C for 4 h. The degassed monomer, catalyst, and the initiator were added to a previously flamed Schlenk tube equipped with a magnetic stirring bar in the given order. The tube was degassed with three FPT cycles, left in argon, and placed in a thermostated oil bath. After the polymerization, the mixture was diluted with THF, and precipitated into an excess amount of cold methanol. The PCL-TEMPO was isolated by filtration and dried at 40 °C in a vacuum oven for 24 h ($[M]_0/[I]_0$ = 20; conv. = 95%; $M_{n,theo}$= 2350 g/mol, $M_{n,GPC}$=

4770 g/mol; M_w/M_n = 1.16, relative to PS standards, $M_{n,PCL}$= 2300 g/mol = 0.259 X $M_{n,GPC}^{1.073}$) DP_n = 19.

3.3.12 Preparation of tadpole (*c*-PS)-*b*-PEG tadpole polymer via NRC click reaction

(*c*-PS)-Br (0.10 g, 0.023 mmol, $M_{n,theo}$ = 4350 g/mol, 1 equiv) was dissolved in DMF (5 mL) in a 10 mL of Schlenk tube. PEG-TEMPO (0.036 g, 0.046 mmol, 2 equiv, $M_{n,theo}$ = 800 g/mol), PMDETA (0.010 mL, 0.046 mmol, 2 equiv), CuBr (0.0060 g, 0.046 mmol, 1 equiv) and Cu(0) (0.014 g, 0.23 mmol, 10 equiv) were added to the solution. The reaction mixture was degassed by three FPT cycles, left in vacuum and stirred overnight at room temperature. After that time, the solution was diluted with THF, filtered through a column filled with neutral alumina to remove copper complex and finally precipitated in methanol. The dissolution-precipitation procedure was repeated two times. The obtained polymer was dried overnight in a vacuum oven at 40 °C (Yield = 0.09 g, 76%; $M_{n,theo}$ = 5050 g/mol (a sum of $M_{n,theo}$ of blocks), $M_{n,NMR}$ = 4350 g/mol, $M_{n,GPC}$ = 3950 g/mol, M_w/M_n =1.09, relative to linear PS). ^{1}H NMR (250 MHz, $CDCl_3$, δ) 7.4-6.2 (Ar*H* of PS), 5.4 (br, 2H, C*H*$_2$-Diels–Alder adduct), 5.0 (br, 2H, C*H*(Ph)-triazole and C*H*O-C=O), 4.7 (br, 1H, C*H*, bridge head proton), 4.2-4.0 (br, 4H, C*H*$_2$OC=OC(CH$_3$)$_2$-TEMPO and PEG-C*H*$_2$OC=O), 4.0-3.0 (br, -OC*H*$_2$C*H*$_2$O, PEG backbone, NC*H*$_2$CH$_2$OC=O, NCH$_2$C*H*$_2$OC=O, C*H*-C*H*, bridge protons, OC*H*$_3$ of PEG and C*H*$_2$OC=OC(CH$_3$)$_2$-PS), 2.9 (br, 2H, triazole-C*H*$_2$CH$_2$C=O), 2.6 (br, 6H, triazole-CH$_2$C*H*$_2$C=O and C=OC*H*$_2$C*H*$_2$C=O), 2.0-0.8 (aliphatic protons of PS, CC*H*$_3$ and CH$_2$OC=O-C(C*H*$_3$)$_2$-PS).

3.3.13 Preparation of (*c*-PS)-*b*-PCL tadpole polymer via NRC click reaction

(*c*-PS)-Br (0.10 g, 0.023 mmol, $M_{n,theo}$ = 4350 g/mol, 1 equiv) was dissolved in DMF (5 mL), in a 10 mL of Schlenk tube. PCL-TEMPO (0.064 g, 0.027 mmol, *M*n,theo =2350 g/mol, 1.2 equiv), PMDETA (0.010 mL, 0.046 mmol, 2 equiv), CuBr (0.0060 g, 0.046 mmol, 1 equiv) and Cu (0) (0.014 g, 0.23 mmol, 10 equiv) were added to the solution. The reaction mixture was degassed by three FPT cycles, left in vacuum and stirred overnight at room temperature. After this specified time, the solution was diluted with THF, filtered through a column filled with neutral alumina to remove copper complex and finally precipitated in methanol/diethyl ether (1:1). The

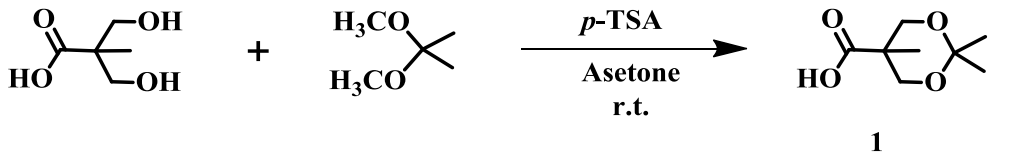
recovered polymer was redissolved in THF and precipitated in methanol at room temperature. The obtained polymer was dried overnight in a vacuum oven at 40 °C (Yield = 0.05 g, 32%; $M_{n,theo}$ = 6700 g/mol (sum of $M_{n,theo}$ of blocks), $M_{n,NMR}$ = 6900 g/mol, $M_{n,GPC}$ = 10200 g/mol, M_w/M_n = 1.05, relative to linear PS). ^{1}H NMR (250 MHz, $CDCl_3$, δ) 7.4-6.2 (Ar*H* of PS), 5.4 (br, 2H, CH_2-Diels-Alder adduct), 5.2-4.8 (br, 2H C*H*(Ph)-triazole and C*H*O-C=O), 4.7 (br, 1H, C*H*, bridge-head proton), 4.0 (br, CH_2OC=O of PCL and CH_2OC=OC$(CH_3)_2$-TEMPO), 3.8-3.0 (br, NC$H_2$$CH_2$OC=O, N$CH_2CH_2$OC=O, C*H*-C*H*, bridge protons, CH_2OH, end group of PCL, and CH_2OC=OC$(CH_3)_2$-PS), 2.8 (br, 2H, triazole-C$H_2$$CH_2$C=O), 2.5 (br, 2H, triazole-CH_2CH_2C=O), 2.3 (br, 2H, C=OCH_2 of PCL), 2.0-0.8 (aliphatic protons of PS, CH_2 of PCL, CCH_3 and CH_2OC=O-C(CH_3)$_2$-PS).

4. RESULTS AND DISCUSSION

Herein we present an efficient synthetic route for the synthesis of tad-pole polymers, (*c*-PS)-*b*-PEG and (*c*-PS)-*b*-PCL, via intramolecular Diels-Alder cyclization reaction between anthracene and maleimide end-groups of the linear PS containing additionally one OH terminal group, subsequent conversion of the hydroxyl into bromide and final NRC reaction with linear TEMPO terminated-PEG (PEG-TEMPO) and -PCL (PCL-TEMPO).

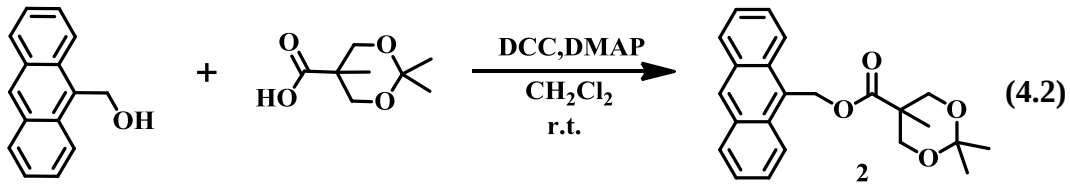
4.1 Synthesis of Initiators

First of all 2,2,5-trimethyl-[1,3]dioxane-5-carboxylic acid **(1)** was synthesized by this way; 2, 2-bis (hydroxymethyl)-propanoic acid was reacted with excess amount of dry acetone using *p*-toluene sulfonic acid as catalyst. Additionally, 2,2-dimethoxy-propane was deliberately used to provide acetone during the reaction. Process is given below schematically (equation 4.1).



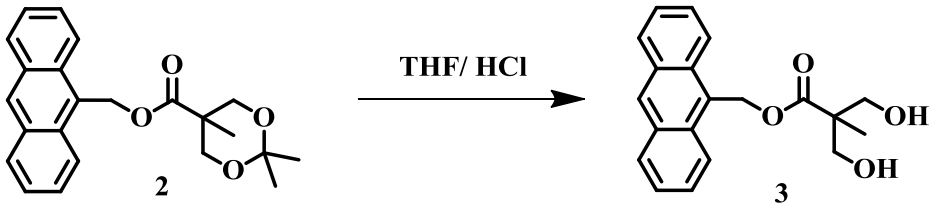
(4.1)

Subsequent esterification reaction between 9-anthracene methanol and **1** was carried out using DCC as a coupling agent and catalytic amount of DMAP as catalyst and to give anthracen-9ylmethyl 2,2,5-trimethyl-1,3-dioxane-5-carboxylate **(2)**. Process is given below schematically (equation 4.2).



(4.2)

Then, hydrolysis of compound **2** was taken placed in THF using dilute HCl to produce anthracen-9ylmethyl 3-hydroxy-2-(hydroxymethyl)-2-methylpropanoate **(3)**. Procedure of the reaction is given below schematically (equation 4.3).



(4.3)

The ^{1}H NMR spectrum of the compounds are shown in Figure 4.1. From the NMR spectrum, the peaks in the range between 3.63 and 4.18 ppm are assigned to methylene protons. The peaks in the range between 1.18 and 1.40 ppm are identified to methyl protons **(1)**. From the NMR spectrum the new signals appeared at δ 8.5-7.5 ppm ArH of anthracene **(2** and **3)**. From the NMR spectrum -O*H* protons **(3)** at δ 2.17 ppm suggests that deprotection step was carried out successfully.

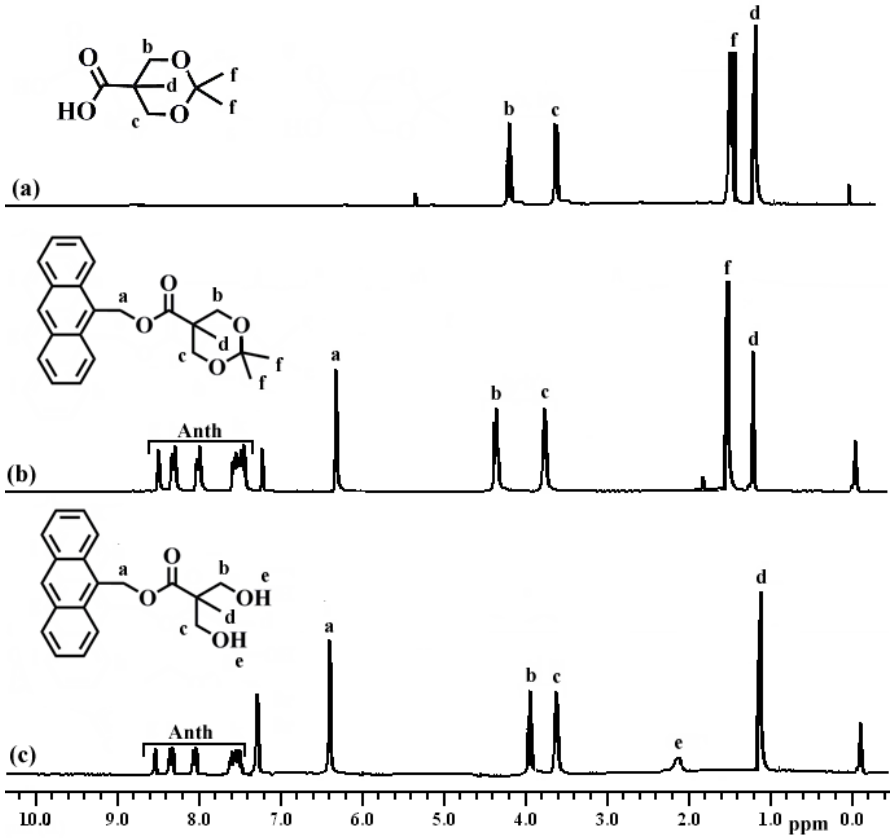
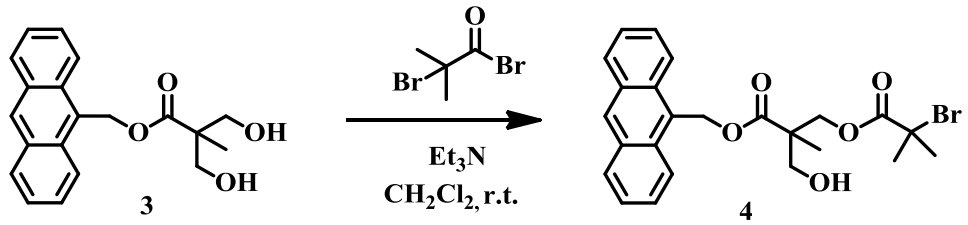


Figure 4.1: ^{1}H NMR spectra of: **a**) 2,2,5-trimethyl-[1,3]dioxane-5-carboxylic acid **(1)**; **b**) anthracen-9ylmethyl 2,2,5-trimethyl-1,3-dioxane-5-carboxylate **(2)**; **c**) anthracen-9ylmethyl 3-hydroxy-2-(hydroxymethyl)-2-methylpropanoate **(3)** in $CDCl_3$.

Finally, the synthesis of anthracen-9-ylmethyl 3-(2-bromo-2-methylpropanoyloxy)-2-(hydroxymethyl)-2-methylpropanoate (**4**) was carried out by the reaction of **3** with 2-bromo-2-methylpropanoyl bromide in the presence of the DMAP, Et_3N and as a solvent THF for 24 hour (equation 4.4).



(4.4)

In this reaction DMAP was used as a catalyst. The existence of HBr was captured by Et_3N as a salt in the solution.

Moreover, It can be seen that 9 H of anthracene unit on ^{1}H NMR spectrum as multiplet peaks are between 7.43–8.52 ppm. Also we can see 6 H of (CH_3)$_2$-C-Br unit as singlet peak at 1.87 ppm. So reaction was succesfully done (Figure 4.2).

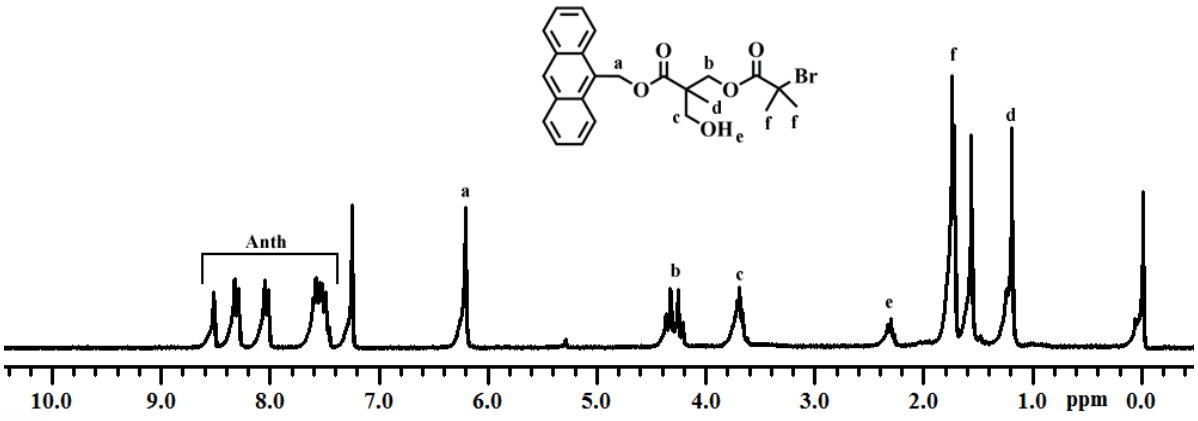
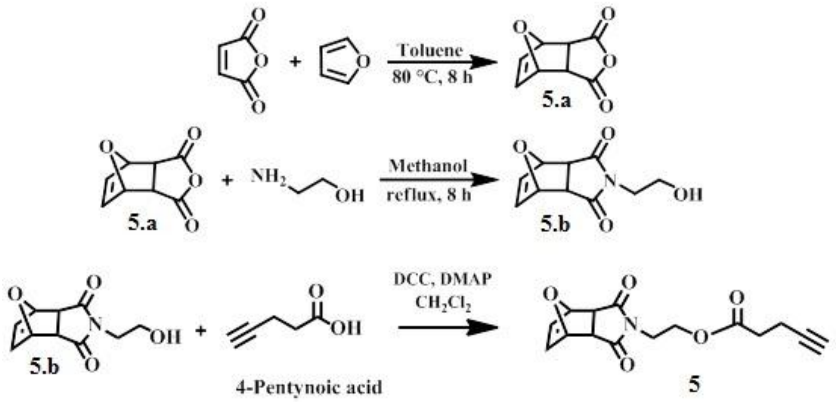


Figure 4.2: ^{1}H NMR spectra of anthracen-9-ylmethyl 3-(2-bromo-2-methylpropanoyloxy)-2-(hydroxymethyl)-2-methylpropanoate (**4**) in $CDCl_3$.

4.2 Synthesis of Linear Anthracene-, OH- and Maleimide-Terminated PS (*l*-α-Anthracene- OH-ω-Maleimide-PS)

Before the synthesis of linear anthracene-, OH- and maleimide-terminated PS (*l*-α-anthracene- OH-ω-maleimide-PS) **5** was synthesized. Furan and maleic anhydride were reacted in toluene at 80 ^{o}C, then the formed adduct (**5.a)** (equation 4.5), was utilized for the synthesis of **5.b** by adding the solution 2-amino ethanol in methanol

into dispersion of **5.a** in methanol (equation 4.5). Finally, **5**, was obtained via an esterification reaction between 4-Pentynoic acid and compound **(5.b)** in CH_2Cl_2. And it was purified by column chromatography over silica gel eluting with ethyl acetate/hexane (1:1) to give **5** as a white solid (Yield: 2.6 g; 94 %) (equation 4.5).



(4.5)

From overlay ^{1}H NMR spectra of **5** as seen in figure 4.3, it was clearly seen that the alkyne proton was detected at 1.95 pmm and the methylene protons next to the ester unit at 4.2 ppm. Moreover, the the characteristic protons of the adduct were also detected at 6.5 ppm (bridge vinyl protons), 5.2 ppm (bridge-head protons) and 2.85 ppm (bridge protons) respectively. These results confirmed that the synthesis of **5** was achived .

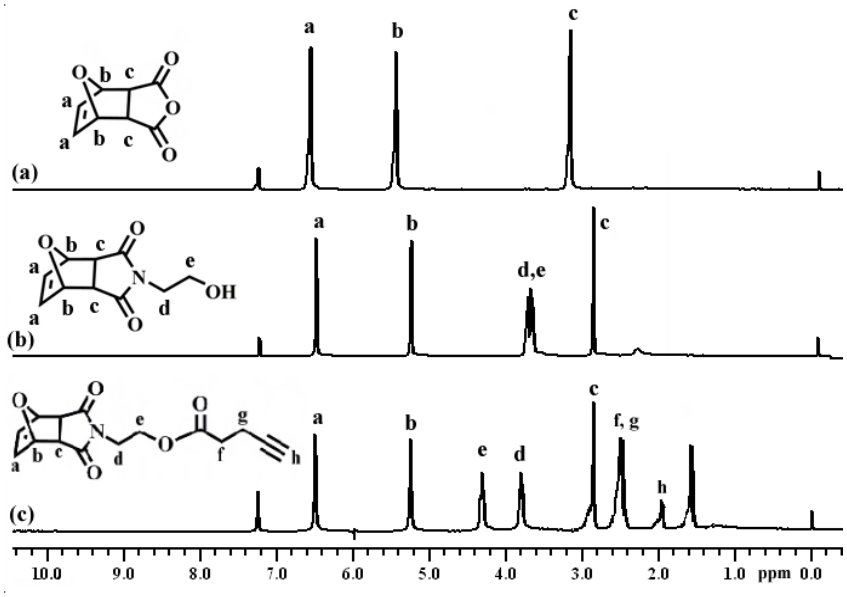
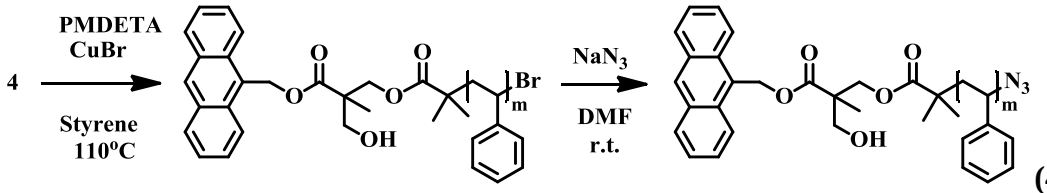


Figure 4.3: ^{1}H NMR spectra of: **a**) 4,10-dioxatricyclo[5.2.1.$0^{2,6}$]dec-8-ene-3,5-dione **(5.a)**; **b**) 4-(2-hydroxyethyl)-10-oxa-4-azatricyclo[5.2.1.$0^{2,6}$]dec-8-ene-3,5-dione (**5.b)**; **c**) Oxanorbornenyl Alkyne **(5)** (c) in $CDCl_3$.

The synthetic pathway for the formation of the linear anthracene, OH, and maleimide terminated PS (*l*-α-anthracene-OH-ω-maleimide-PS) required two steps. Firstly, the linear anthracene-, OH- and bromide-terminated PS **(***l*-α-anthracene-OH-ω-bromide-PS) was achieved by using **4** as initiator in ATRP of St in the presence of CuBr/PMDETA at 110 ^{o}C for 25 min, followed by the transformation of the bromide end functionality to the azido in order to give the linear anthracene-, OH- and azide-terminated PS (*l*-α-anthracene-OH-ω-azide-PS) (equation 4.6).



(4.6)

The GPC and ^{1}H NMR spectroscopy confirmed that all polymers were properly prepared with controlled molecular weight, low molecular weight distribution (M_w/M_n) and desired end-group functionalities. The DP_n = 33 and the number-average molecular weight by NMR ($M_{n,NMR}$ = 3900 g/mol) of *l*-α-anthracene-OH-ω-bromide-PS was determined by an integrated ratio of the signals at 7.5-6.0 (Ar*H* of PS) and 8.0 ppm (2 Ar*H* protons of anthracene). The $M_{n,GPC}$ of this polymer was 3700 g/mol with a M_w/M_n of 1.18 as determined by GPC relative to linear PS standards, which was comparable to the $M_{n,NMR}$. The substitution of the bromide end-group of the *l*-α-anthracene-OH-ω-bromide-PS with the azide was monitored by disappearance of the C*H*(Ph)Br end-group signal at 4.4 ppm and by appearance of C*H*(Ph)N_3 signal at 3.9 ppm by ^{1}H NMR (Figure 4.4, 4.5). The GPC analysis of the *l*-α-anthracene-OH-ω-azide-PS yielded a $M_{n,GPC}$ = 3850 g/mol with a M_w/M_n = 1.15 based on calibration with linear PS standards.

In the next step, the azide end-group was quantitatively converted to maleimide end-group with the CuAAC click reaction between the *l*-α-anthracene-OH-ω-azide-PS and **5** catalyzed by PMDETA/CuBr in DMF at room temperature. In this reaction, 3 equiv of **5** relative to that of the *l*-α-anthracene-OH-ω-azide-PS was deliberately employed to ensure the reaction completion and the easy removal of **5** from the reaction mixture by dissolution-precipitation procedure (equation 4.7).

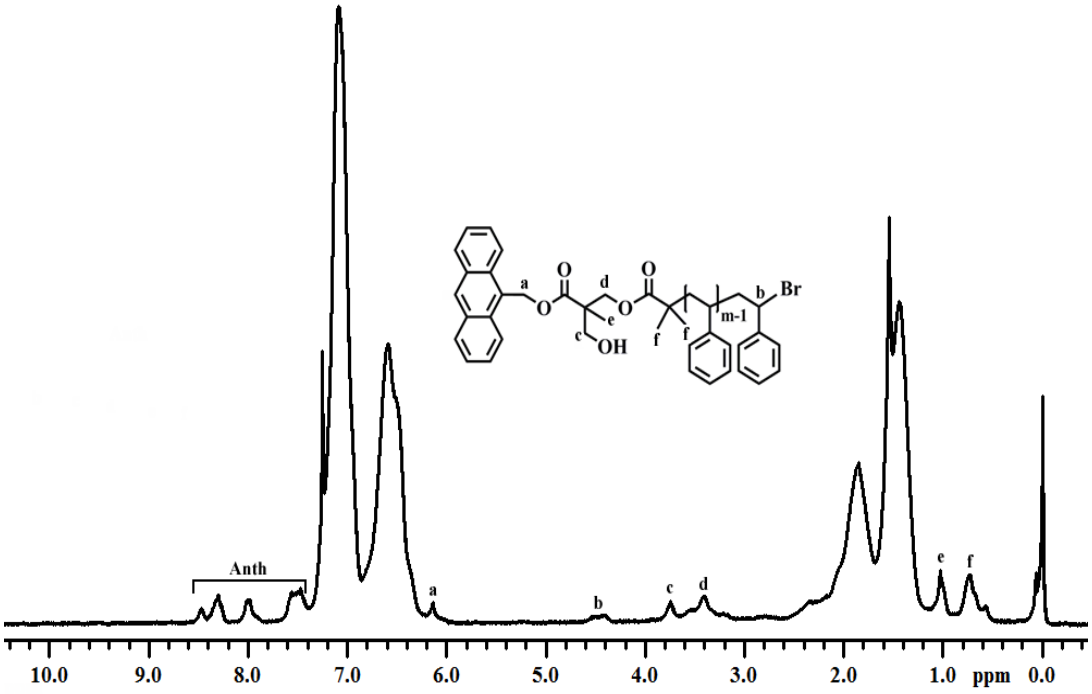


Figure 4.4: ^{1}H NMR spectra of the linear anthracene-, OH- and bromide-terminated PS **(***l*-α-anthracene-OH-ω-bromide-PS) in $CDCl_3$.

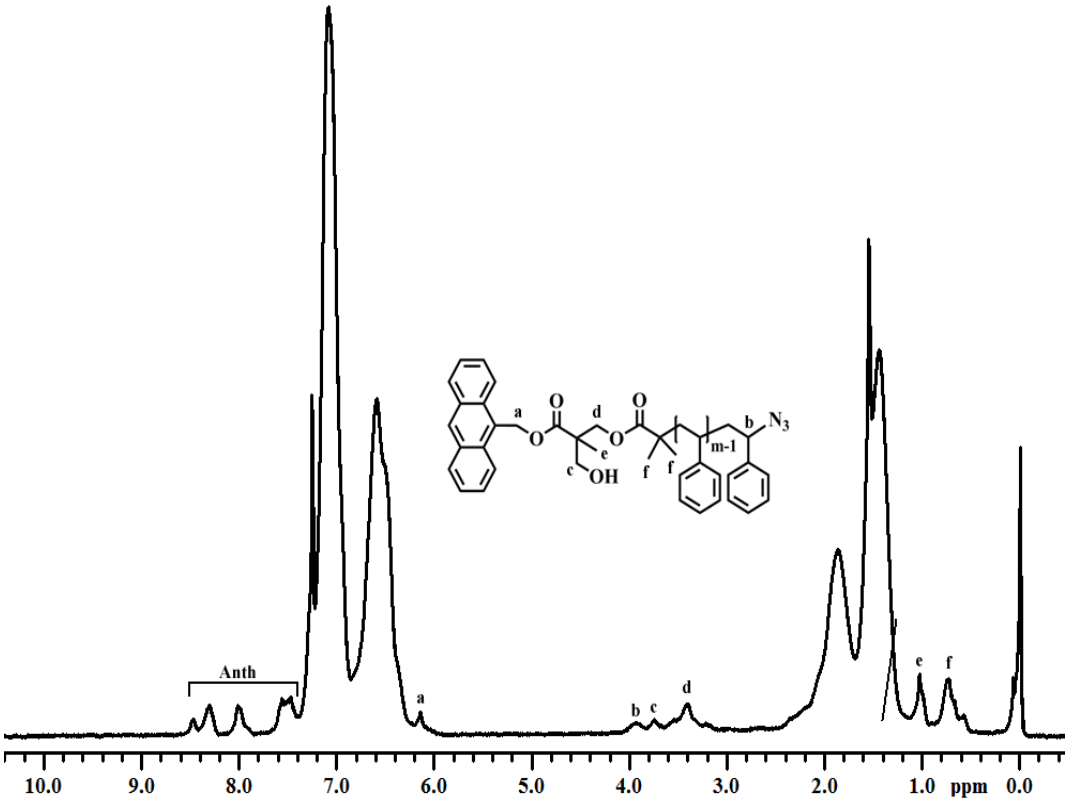
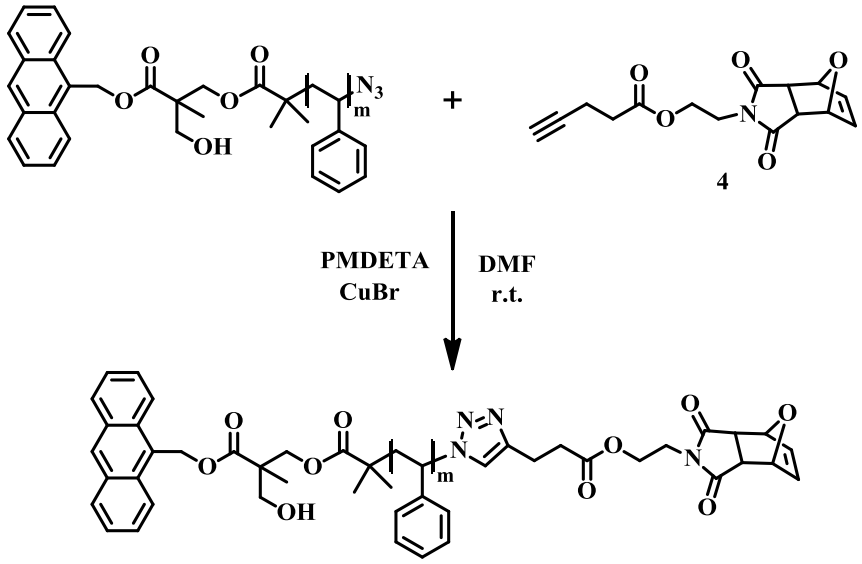


Figure 4.5: ^{1}H NMR spectra of the linear anthracene-, OH- and azide-terminated PS (*l*-α-anthracene-OH-ω-azide-PS) in $CDCl_3$.



(4.7)

The ^{1}H NMR spectrum of *l*-α-anthracene-OH-ω-maleimide-PS confirmed the evidence of maleimide group introduction as an end-group with the CuAAC click reaction by appearance of the characteristic signals of the maleimide bridge-head protons at 5.2 and CH(Ph) proton next to the triazole ring at 5.1 ppm (Figure 4.6). Moreover, the signals at 4.2 and 2.8 ppm might be assigned to the $NCH_2CH_2OC=O$, and the triazole-$CH_2CH_2C=O$ and the bridge- protons ($CH_2NC=OCH$-CH), respectively. An integration of the anthracene-CH_2 signals to the bridge-protons also confirmed the structure and thus, the quantitative CuAAC reaction.

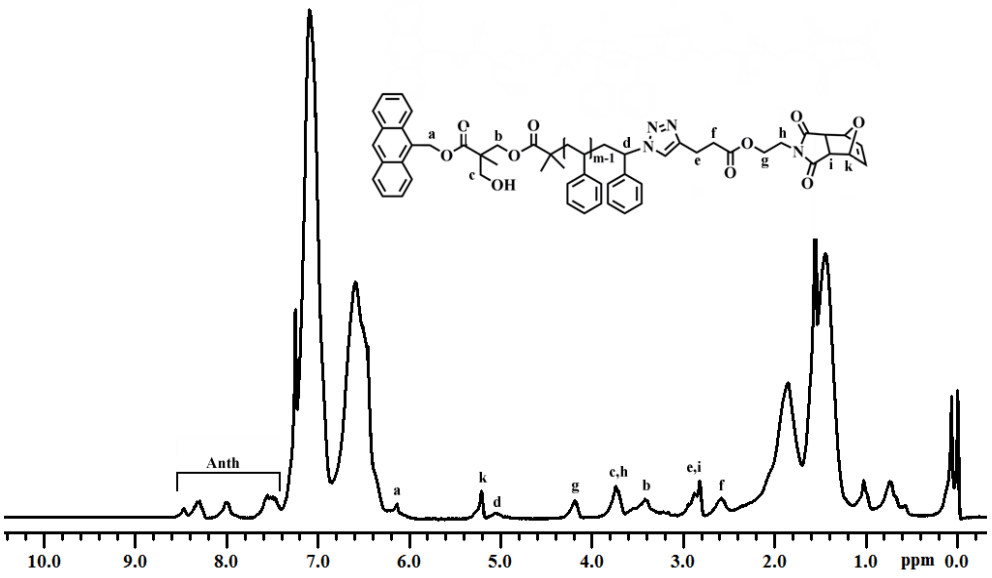
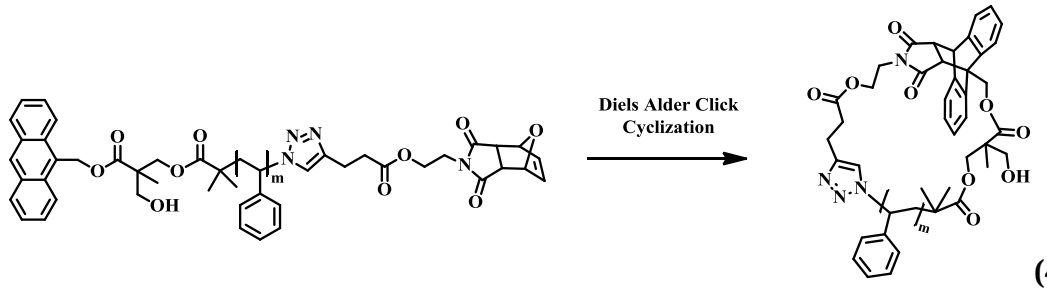


Figure 4.6: ^{1}H NMR spectra of the linear anthracene, OH, and maleimide terminated PS (*l*-α-anthracene-OH-ω-maleimide-PS) in $CDCl_3$.

4.3 The Cyclization Reaction via Intramolecular Diels-Alder Click Reaction

The cyclization reaction via intramolecular Diels-Alder click reaction was carried out by refluxing the linear precursor, *l*-α-anthracene-OH-ω-maleimide-PS in toluene at a concentration of 3 X 10^{-4} M for 48 h to yield the cyclic-PS with a OH functional group ((c-PS)-OH) (equation 4.8).



(4.8)

The crude product was purified via a dissolution-precipitation initially in THF-methanol/diethyl ether (2/1) to remove the linear polymer precursors and subsequently in THF-methanol. The cyclization was monitored by ^{1}H NMR and GPC measurements. ^{1}H NMR spectrum of the purified (*c*-PS)-OH displayed no signals at 8.5-8.0 and 6.1 ppm regarding the anthracene Ar*H*s and the CH_2 protons linked to the anthracene, respectively (Figure 4.7). The successful cyclization was further confirmed by appearance of the OCH_2 linked to the Diels-Alder adduct at 5.4 and the C*H* bridge-head proton at 4.8 ppm.

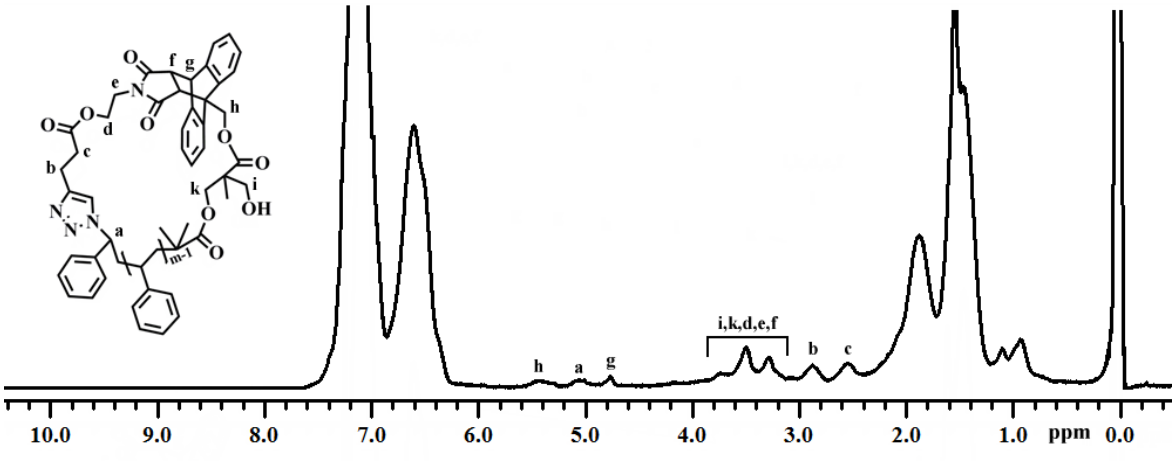


Figure 4.7: ^{1}H NMR spectra of the cyclic-PS with a OH functional group ((c-PS) OH) in $CDCl_3$.

The overlay of the GPC traces of (*c*-PS)-OH and its linear precursor can also afford an evidence of the successful cyclization (Figure 4.8). It was observed that the monomodal GPC trace of (*c*-PS)-OH shifted to a higher retention time with respect

to its linear precursor (*l*-α-anthracene-OH-ω-maleimide-PS), because a cyclic structure has a more compact topology resulting in a lower hydrodynamic volume compared with its linear counterpart.

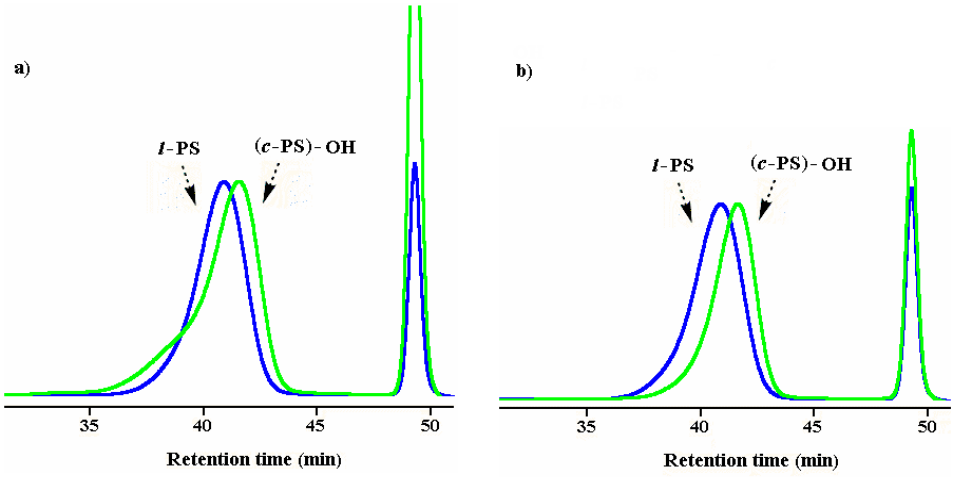


Figure 4.8: GPC traces of *l*-PS and (*c*-PS)-OH **a)** before purification. **b)** after purification.

The (*c*-PS)-OH and its linear precursor was further analyzed by TD-GPC measurements affording the $M_{n,TDGPC}$, intrinsic viscosity ([η]), and hydrodynamic radius (R_h) values depending on that the dn/dc = 0.185 mL/g of linear PS is equal to that of cyclic PS. It should be noted that the $M_{n,TDGPC}$ = 4140 g/mol; M_w/M_n = 1.20 and $M_{n,TDGPC}$ = 4200 g/mol; M_w/M_n = 1.28 are calculated for (*c*-PS)-OH and its linear precursor, respectively. Additionally, [η] = 0.051 dL/g and R_h = 1.6 nm values of the (*c*-PS)-OH were found to be lower than those of the linear precursor ([η] = 0.074 dL/g and R_h = 1.8 nm), due to a more compact topology of the cyclic polymer (Table 4.1). The ratio of the [η] value of (*c*-PS)-OH to that of linear precursor was 0.69, which is comparable to literature values for macrocycles (0.66-0.69) [129, 130].

Diels-Alder click reaction efficiency was also monitored by UV spectroscopy after the decrease in absorbance of anthracene between 300 and 400 nm in the reaction medium as seen in figures 4.9. Diels–Alder efficiency was calculated by following anthracene Conv. % = $(1 - A_t/A_0)$, where A_0 and A_t are initial and final absorbance values of anthracene and at 0.5 g/ L. Diels-Alder click reaction efficiencies were calculated by monitoring the disappearance of the signals corresponding to the anthracene group and found to be 95 % (Figure 4.9).

Table 4.1: The results of (*c*-PS)-OH and its linear precursor (*l*-α-anthracene-OH-ω maleimide-PS)

Polymer	Conv.[c] (%)	TD-GPC				
		M_n (g/mol)	M_w/M_n	d*n*/d*c* (mL/g)	[η] (dL/g)	R_h (nm)
***l*-α-anthracene-OH-ω-maleimide-PS**[a]	90	4200	1,28	0.185	0.074	1,8
(*c*-PS)-OH[b]	95	4140	1,2	0.185	0.051	1,6

[a] The CuAAC click reaction between the *l*-α-anthracene-OH-ω-azide-PS and **5** catalyzed by PMDETA/CuBr in DMF at room temperature.

[b] The cyclization reaction via intramolecular Diels-Alder click reaction was carried out by refluxing the linear precursor, *l*-α-anthracene-OH-ω-maleimide-PS in toluene to produce (*c*-PS)-OH.

[c] Determined by gravimetrically.

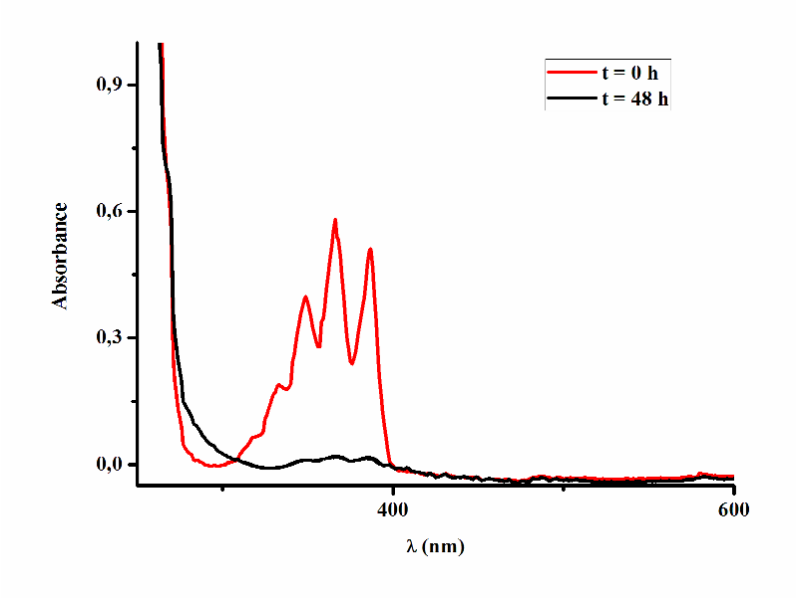
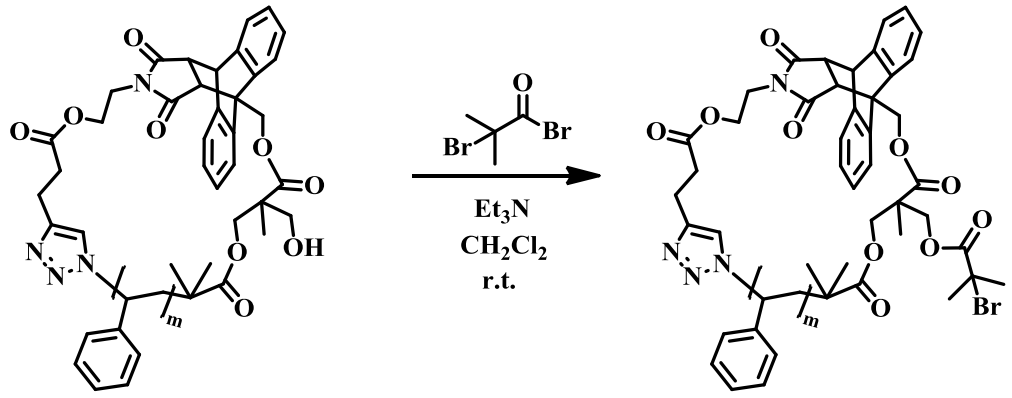


Figure 4.9: UV spectra to monitor the efficiency of intramolecular Diels-Alder reaction of *l*-α-anthracene-OH-ω-maleimide-PS after 0 h and 48 h in CH_2Cl_2.

In a following step, the bromide functionality was introduced to the PS cycle via an esterification reaction between (*c*-PS)-OH and 2-bromoisobutryl bromide to yield the (*c*-PS)-Br (equation 4.9).

The ^{1}H NMR spectrum of (*c*-PS)-Br exhibits one new ester C*H*$_2$ at 4.2 ppm, characteristic of the formation of one bromide functionality per PS ring (Figure 4.10). The integration ratio of these two hydrogens to the Ar*H*s of PS confirmed the expected structure for the (*c*-PS)-Br.



(4.9)

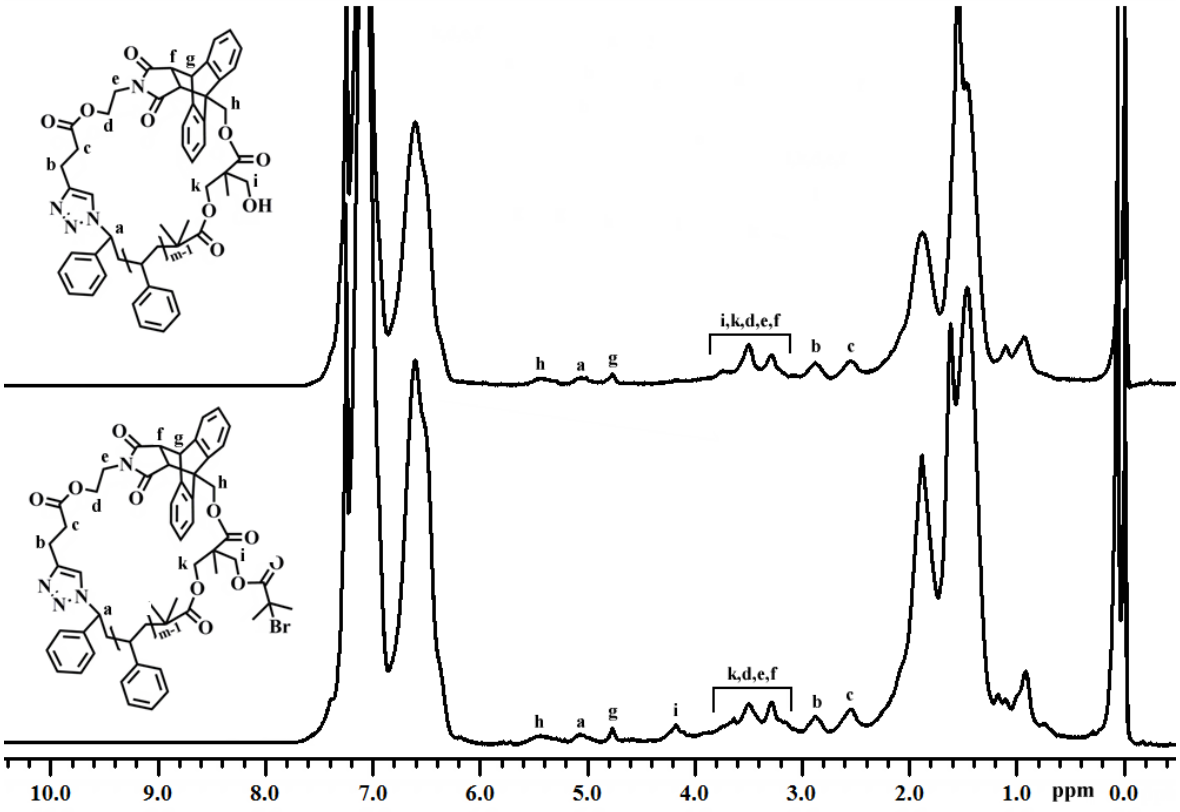
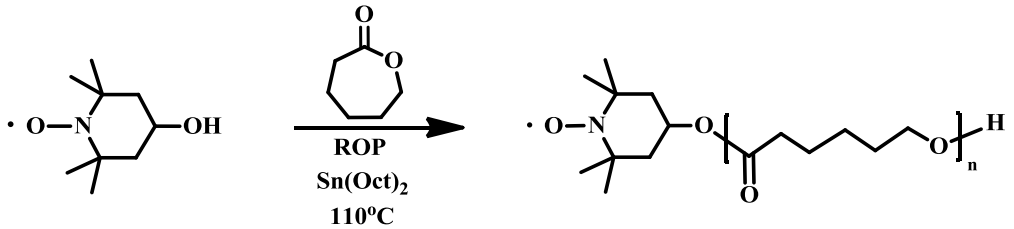


Figure 4.10: ^{1}H NMR spectra of the cyclic-PS with a OH functional group ((c-PS)-OH) and cyclic-PS with a bromide functional group ((c-PS)-OH) in $CDCl_3$.

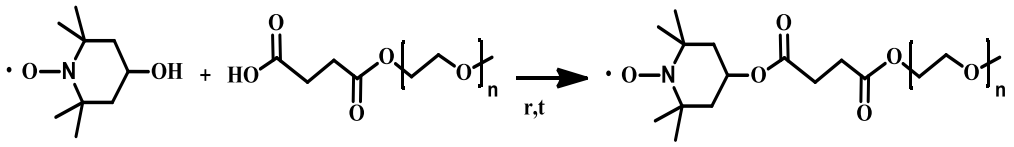
4.4 Preparation of Tadpole (*c*-PS)-*b*-PEG and (*c*-PS)-*b*-PCL Tadpole Polymers via NRC Click Reaction

TEMPO-PCL was prepared by Ring Opening Polymerization(ROP) of ε-CL (in bulk using tin(II)-2-ethylhexanoate as a catalyst and 4-hyroxy-TEMPO as an initiator at 110 °C (equation 4.10).



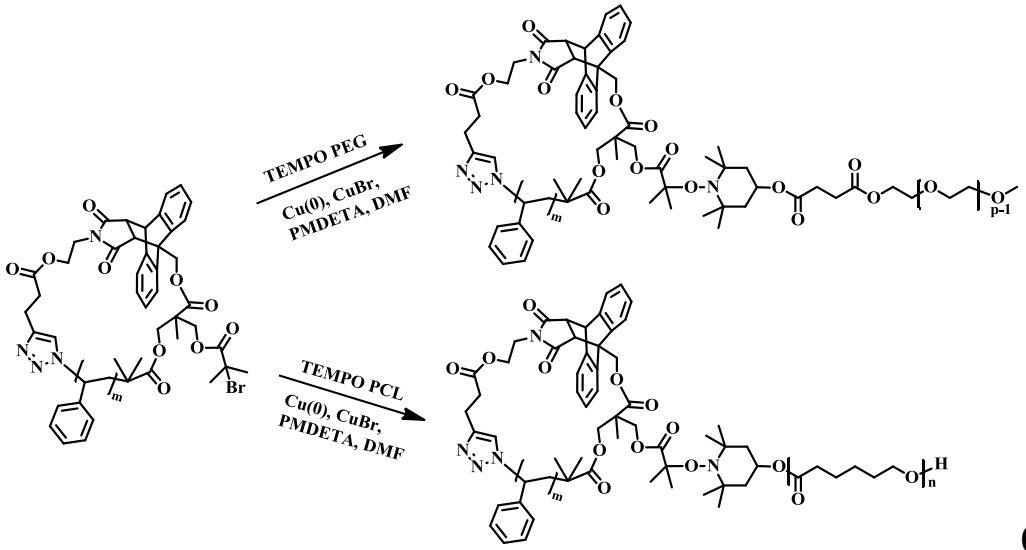
TEMPO-PCL **(4.10)**

Next, TEMPO-PEG was obtained from reaction of PEG-COOH using 4-hyroxy-TEMPO as an initiator (equation 4.11).



PEG-COOH TEMPO-PEG **(4.11)**

The (*c*-PS)-Br was subsequently clicked with either a linear PEG-TEMPO or a PCL-TEMPO precursor via the NRC reaction resulting in a tadpole polymer, (*c*-PS)-*b*-PEG or (*c*-PS)-*b*-PCL (equation 4.12).



(4.12)

The successful incorporation of these linear precursors was confirmed by the appearance of the CH_2CH_2O signal of PEG backbone at 3.6 ppm and CH_2OC=O and the C=OCH_2 signals of PCL backbone at 4.0 and 2.3 ppm, respectively along with the signals of cyclic PS (Figures 4.11 and 4.12).

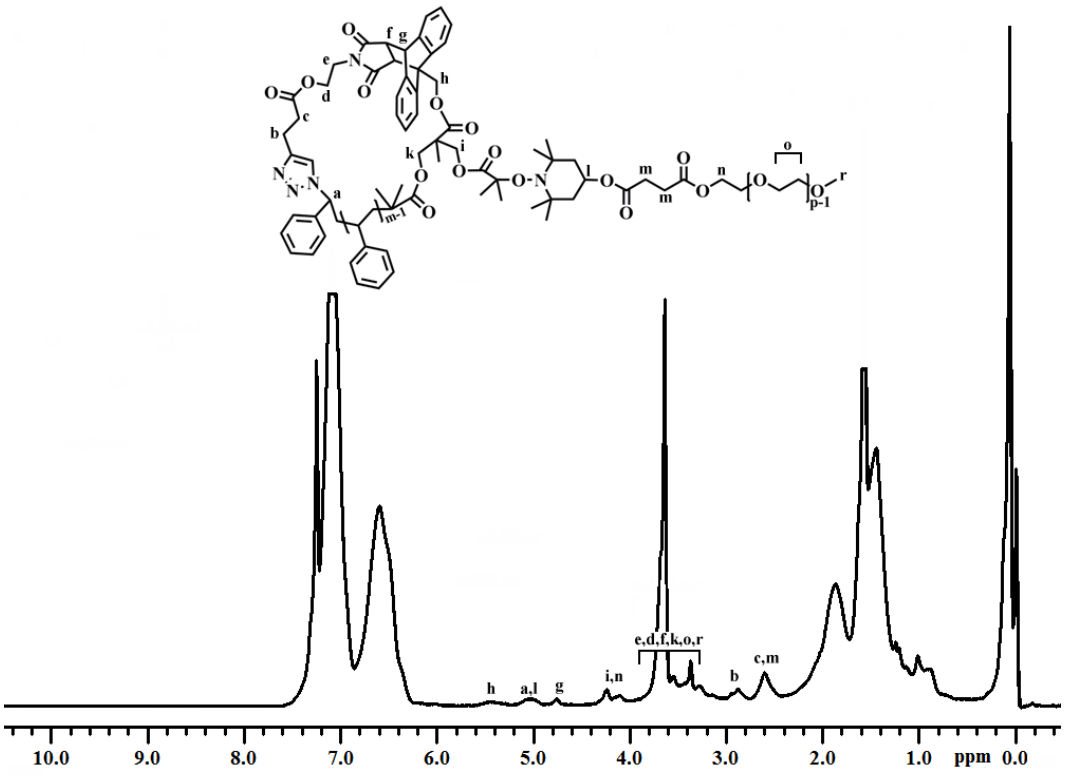


Figure 4.11: ^{1}H NMR spectra of (*c*-PS)-*b*-PEG in $CDCl_3$.

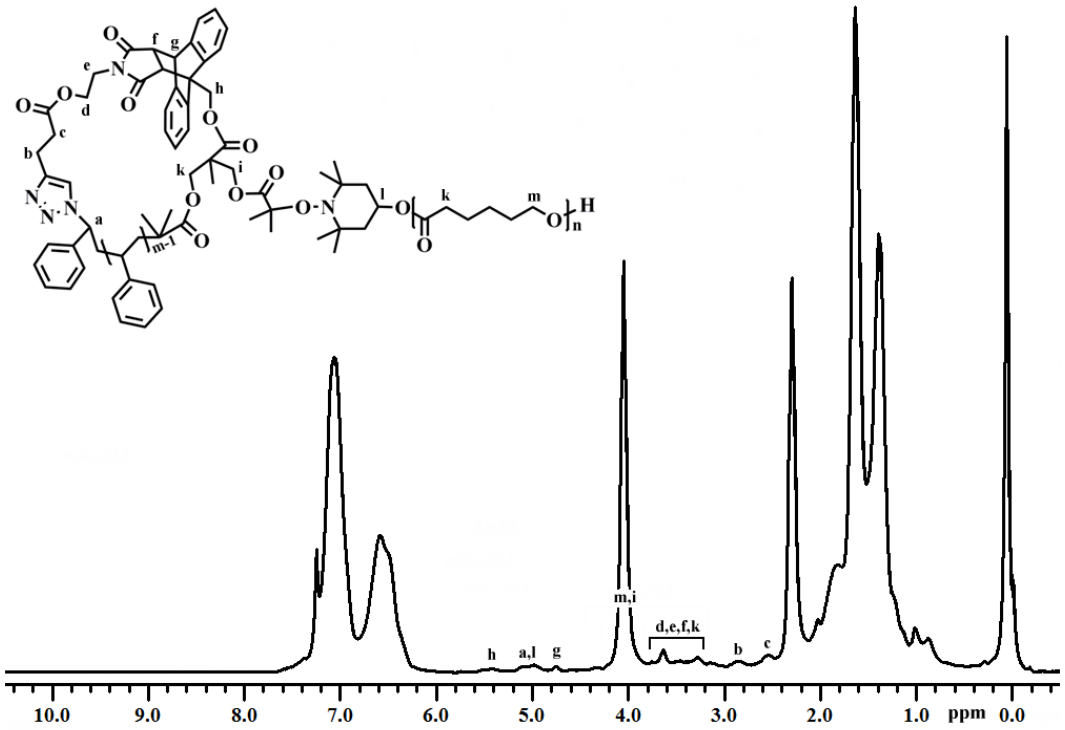


Figure 4.12: ^{1}H NMR spectra of (*c*-PS)-*b*-PCL in $CDCl_3$.

If the DP_n of the linear PS block is assumed to be 33, the resonance intensity ratios of the Ar*H*s of PS versus the CH_2CH_2O of PEG and versus the CH_2OC=O of PCL gave the DP_n = 10 of the PEG and the DP_n = 23 of PCL in the tadpole product. These were in rather good agreement with those of linear precursors, DP_n = 13 and 19, respectively. The GPC traces of tadpole polymers demonstrate a monomodal distribution and a clear shift to a lower retention time with respect to their both cyclic and linear precursors (Figures 4.13 and 4.14).

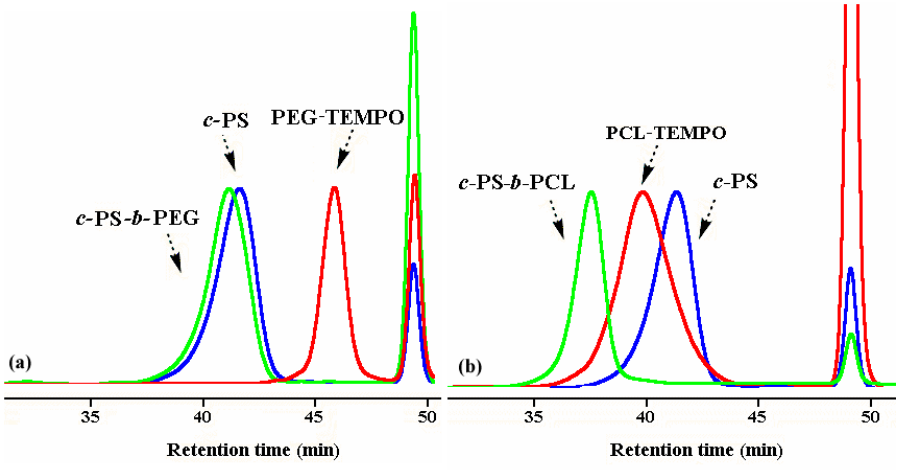


Figure 4.13: The evolution of GPC traces: **a)** *c*-PS, PEG-TEMPO and (*c*-PS)-*b*-PEG. **b)** *c*-PS, PCL-TEMPO and (*c*-PS)-*b*-PCL.

The molecular weight details of all block copolymers after NRC click reaction were tabulated in table 4.2.

Table 4.2: The results of the tadpole polymers via NRC click reaction.

Polymer	Precursors	$M_{n,GPC}$ (g/mol)	M_w/M_n	$M_{n,theo}$[a] (g/mol)	$M_{n,NMR}$[b] (g/mol)
(*c*-PS)-*b*-PEG	*c*-PS + PEG-TEMPO	3950	1.09	5050	4350
(*c*-PS)-*b*-PCL	*c*-PS + PCL-TEMPO	10200	1.05	6700	6900

[a] .$M_{n,theo}$ = sum of $M_{n,NMR}$ of blocks.

[b] $M_{n,NMR}$ of the block copolymers were calculated by taking into account a ratio of the integrated values of the *c*-PS (DP_n = 33) to the PEG and PCL segments

5. CONCLUSION

In this study, a combination of the CuAAC and the Diels-Alder click reactions enabled to form the cyclic PS with one OH on the ring, (*c*-PS)-OH. The *c*-PS-OH was further reacted with 2-bromoisobutryl bromide to yield the cyclic PS with one bromide functionality, (*c*-PS)-Br. and subsequent NRC click reaction with either well-defined TEMPO-PEG or TEMPO-PCL afforded the target tadpole polymer, (*c*-PS)-*b*-PEG or (*c*-PS)-*b*-PCL.

The GPC traces of the resulting tadpole polymers exhibited a monomodal distribution and a clear shift to higher molecular weight region relative to their precursors. It should be noted that the triple click reaction methodology employed here provides a simple and an efficient way to produce tadpole polymers with various compositions.

REFERENCES

[1] **Altintas, O.; Vogt, A. P.; Barner-Kowollik, C.; Tunca, U.,** 2012. 3-miktoarm star terpolymers using triple click reactions: Diels–Alder, copper-catalyzed azide-alkyne cycloaddition, and nitroxide radical coupling reactions. Journal of Polymer Science Part A**:** Polymer Chemistry Review DOI: 10.1039/C1PY00249J

[2] **Davis, K. A.; Matyjaszewski, K.**, 2002. Statistical, gradient, block, and graft copolymers by controlled/living radical polymerizations. In *Statistical, gradient, block and graft copolymers by controlled/living radical polymerizations*, Vol. 159, pp 1-169.

[3] **Kamigaito, M.; Ando, T.; Sawamoto, M.**, 2001. Metal-catalyzed living radical polymerization. *Chemical Reviews* 101, (12), 3689-3746.

[4] **Yagci, Y.; Atilla Tasdelen, M.**, 2006. Mechanistic transformations involving living and controlled/living polymerization methods. *Progress in Polymer Science* 31, (12), 1133-1170.

[5] **Chiefari, J.; Chong, Y. K.; Ercole, F.; Krstina, J.; Jeffery, J.; Le, T. P. T.; Mayadunne, R. T. A.; Meijs, G. F.; Moad, C. L.; Moad, G.; Rizzardo, E.; Thang, S. H.**, 1998. Living free-radical polymerization by reversible addition-fragmentation chain transfer: The raft process. *Macromolecules* 31, (16), 5559-5562.

[6] **Georges, M. K.; Veregin, R. P. N.; Kazmaier, P. M.; Hamer, G. K.**, 1993. Narrow molecular weight resins by a free-radical polymerization process. *Macromolecules* 26, (11), 2987-2988.

[7] **Kato, M.; Kamigaito, M.; Sawamoto, M.; Higashimura, T.**, 1995. Polymerization of methyl methacrylate with the carbon tetrachloride dichlorotris (triphenylphosphine) ruthenium(II) methylaluminum bis(2,6-di-tert-butylphenoxide) initiating system possibility of living radical polymerization. *Macromolecules* 28, (5), 1721-1723.

[8] **Wang, J. S.; Matyjaszewski, K.**, 1995. Living controlled radical polymerization transition metal catalyzed atom transfer radical polymerization in the presence of a conventional radical initiator. *Macromolecules* 28, (22), 7572-7573.

[9] **Percec, V.; Barboiu, B.**, 1995. Living radical polymerization of styrene initiated by arenesulfonyl chlorides and Cu-I(bpy)(n)cl *Macromolecules* 28, (23), 7970-7972.

[10] **Lin,W., Fu, Q., Zhang, Y., Huang, J.,** 2008, One-Pot Synthesis of ABC Type Triblock Copolymers via a Combination of "Click Chemistry" and Atom Transfer Nitroxide Radical Coupling Chemistry, Macromolecules, 41, 4127-4137

[11] **Kolb, H. C.; Finn, M. G.; Sharpless, K. B.**, 2001. Click chemistry: Diverse chemical function from a few good reactions. *Angewandte Chemie International Edition* 40, (11), 2004-2021.

[12] **Laurent, B. A.; Grayson, S. M**., 2009. Synthetic approaches for the preparation of cyclic polymers, Chem Soc Rev, 38, 2202-2213.

[13] **Kricheldorf, H. R**., 2010. Cyclic polymers: Synthetic strategies and physical properties, J Polym Sci Part A: Polym Chem 48: 251–284.

[14] **Yamamoto, T.; Tezuka, Y.,** 2011. Topological polymer chemistry: a cyclic approach toward novel polymer properties and functions, Polym. Chem., **2**, 1930–1941.

[15] **Hizal, G.; Tunca, U.; Sanyal, G**., 2011. Discrete macromolecular constructs via the Diels–Alder "Click" reaction, J Polym Sci Part A 49: 4103–4120.

[16] **Hall, D. J.; Van Den Berghe H. M.; Dove A. P**., 2011. Synthesis and post-polymerization modification of maleimide-containing polymers by 'thiol-ene' click and Diels–Alder chemistrie, Polym Int , **60**, 1149– 1157.

[17] **Kempe, K.; Krieg, A.; Becer, C. R.; Schubert U. S.,** 2011. Chemical Society Reviews, **DOI:** 10.1039/C1CS15107J

[18] **Mızawa, T.; Takenaka, K., Shıomı, T**., 2000. Synthesis of α-maleimide-ω-dienyl heterotelechelic poly(methyl methacrylate) and its cyclization by the intramolecular Diels–Alder reaction, J Polym Sci A: Polym Chem 38: 237–246.

[19] **Laurent, B. A.; Grayson, S. M**., 2006**.** An Efficient Route to Well-Defined Macrocyclic Polymers via "Click" Cyclization, J. Am. Chem. Soc. 128, 4238-4239

[20] **Li, H.; Riva, R.; Jerome, R.; Lecomte, P.,** 2007. Combination of Ring-Opening Polymerization and 'Click' Chemistry for the Synthesis of an Amphiphilic Tadpole—Shaped Poly(ε-Caprolactone) Grafted by PEO, Macromolecules, **40**, 824- 831.

[21] **Xu, J.; Ye, J.; Liu, S.,** 2007. Macromolecules, **40**, 9103-9110.

[22] **Qiu, X.-P.; Tanaka, F.; Winnik, F. o. M.,** 2007. Macromolecules, **40**, 7069-7071.

[23] **Shi, G. Y.; Tang, X. Z.; Pan, C. Y.,** 2008. Tadpole-shaped amphiphilic copolymers prepared via RAFT polymerization and click reaction, J Polym Sci Part A: Polym Chem 46: 2390–2401.

[24] **Shi, G. Y.; Pan, C. Y.,** 2008. Macromol. Rapid Commun., 29, 1672–1678

[25] **Li, L. Y.; He, W. D.; Lı, J.; Han, S. C.; Sun, X. L.; Zhang, B. Y., 2009**. JPolym Sci Part A: Polym Chem 47: 7066–7077.

[26] **Dong, Y. Q.; Tong, Y. Y.; Dong, B. T.; Du, F. S.; Li, Z. C.,** 2009. Macromolecules, *42*, 2940-2948.

[27] **Misaka, H.; Kakuchi, R.; Zhang, C.; Sakai, R.; Satoh, T.; Kakuchi, T.,**2009. Synthesis of Well-Defined Macrocyclic Poly(delta-valerolactone) by 'Click Cyclization', Macromolecules, 42, 5091–5096.

[28] **Clark, P. G.; Guidry, E. N.; Chan, W. Y.; Steinmetz, W. E., Grubbs, R.H.,** 2010. "Synthesis of a Molecular Charm Bracelet via Click Cyclization and Olefin Metathesis Clipping." J. AM. CHEM. SOC., *132*, 3405–3412.

[29] **Lonsdale, D. E.; Monteiro, M. J.,** 2010. Chem. Commun., **46**, 7945–79477945.

[30] **Han, D.; Tong, X.; Zhao, Y.; Galstian, T.; Zhao, Y.,** 2010. Cyclic Azobenzene-Containing Side-Chain Liquid Crystalline Polymers: Synthesis and Topological Effect on Mesophase Transition, Order, and Photoinduced Birefringence**,** Macromolecules, **43**, 3664-3671.

[31] **Stanford, M.J.; Pflughaupt, R.L.; Dove, A.P.,** 2010. Synthesis of Stereoregular Cyclic Poly(lactide)s via "Thiol−Ene" Click Chemistry, Macromolecules **43**: 6538–6541.

[32] **Durmaz, H.; Dag, A.; Hızal, G.; Tunca, U.,** 2010. Cyclic homo and block copolymers through sequential double click reactions, J Polym Sci Part A: Polym Chem 48: 5083–5091.

[33] **Aimetti, A. A.; Shoemaker, R. K.; Lin, C. C.; Anseth, K. S.,** 2010. On-resin peptide macrocyclization using thiol-ene click chemistry. Chem Commun, **46**, 4061.

[34] **Wan, X.; Liu, T.; Liu, S.,** 2011. Synthesis of Amphiphilic Tadpole-Shaped Linear-Cyclic Diblock Copolymers via Ring-Opening Polymerization Directly Initiating from Cyclic Precursors and Their Application as Drug Nanocarriers, Biomacromolecules, 12, 1146–1154.

[35] **Lonsdale, D. E.; Monteiro, M. J.,** 2011. Synthesis and self-assembly of amphiphilic macrocyclic block copolymer topologies, J Polym Sci Part A: Polym Chem 49: 4603–4612.

[36] **Nicolay, R.; Matyjaszewski K.,** 2011. Synthesis of Cyclic (Co)polymers by Atom Transfer Radical Cross-Coupling and Ring Expansion by Nitroxide-Mediated Polymerization, Macromolecules, 44, 240-247.

[37] **Schmidt, B. V. K. J.; Fechler, N.; Falkenhagen, J.; Lutz, J.-F.**, 2011. Controlled folding of synthetic polymer chains through the formation -of positionable covalent bridges, Nat. Chem, **3**, 234-238.

[38] **Touris, A.; Hadjichristidis, N.,** 2011. Cyclic and Multiblock Polystyrene-*block*-polyisoprene Copolymers by Combining Anionic Polymerization and Azide/Alkyne "Click" Chemistry, Macromolecules, CuAAC Click, 44, 1969–1976.

[39] **Glassner, M.; Blinco, J. P.;** Barner-Kowollik, C., 2011. Diels–Alder Reactions as an Efficient Route to High Purity Cyclic Polymers, Macromol Commun, 32, 724–728.

[40] **Gang-Yin, S.; Xue-Zhi, T.; Cai-Yuan, P.,** 2007 Tadpole-Shaped Amphiphilic Copolymers Prepared via RAFT Polymerization and Click Reaction 1,2.

[41] **Szwarc, M.,** 1956. Block copolymers, *Nature*, **178**, 1168.

[42] **Quirk, R. P.; Kinning, D. J.; Fetters, L. J.,** 1989. Comprehensive Polymer Science, Aggarwal, S. L., Vol 7, p.1, Ed. Pergamon Press, London.

[43] **Matyjaszewski, K.,** 1995. Introduction to Living Polymerization, Living and/or Controlled Polymerization, *J. Phys. Org. Chem.*, **8(4),** 197-207.

[44] **Percec, V.; Tirrel, D. A.,** 2000. Living or Controlled , *J. Polym. Sci., Part A: Org. Ppoly Chem.*, **38(10),** 1705-1752.

[45] **Quirk, R.; Lee, B.,** 1992. Terminology and classification of quasiliving polymerizations and ideal living polymerizations on the basis of the logic of elementary polymerization reactions, and comments on using the term controlled,.4. *Polym. Int.*, **27,** 359.

[46] **Matyjaszewski, K.; Lin, C. H.,** 1991. Naming of controlled, living polymerizations, *Makromol. Chem. Macromolecules Symp.*, **47**, 221.

[47] **Litvinienko, G.; Müler, A. H. E.,** 1997. General kinetic analysis and comparison of molecular weight distributions for various mechanisms of activity exchange in living polymerizations, *Macromolecules*, **30**, 1253.

[48] **Wang, J.S.; Matyjaszewski, K.**, 1995, Controlled living radical polymerization - atom-transfer radical polymerization in the presence of transition-metal complexes, *Journal of the American Chemical Society*, **117,** 5614-5615.

[49] **Kato, M.; Kamigaito, M.; Sawamoto, M.; Higashimura, T.,** 1995, Polymerization of methyl-methacrylate with the carbon-tetrachloride dichlorotris (triphenylphosphine) ruthenium(ii) methylaluminum bis(2,6-di-tert-butylphenoxide) initiating system - possibility of living radical polymerization, *Macromolecules*, **28,** 1721-1723.

[50] **Georges, M.K.; Veregin, R.P.N.; Kazmaier, P.M.; Hamer, G.K.**, 1993, Narrow molecular-weight resins by a free-radical polymerization process, *Macromolecules*, **26,** 2987-2988.

[51] **Chiefari, J.; Chong, Y.K.; Ercole, F.; Krstina, J.; Jeffery, J.; Le, T.P.T.; Mayadunne, R.T.A.; Meijs, G.F.; Moad, C.L.; Moad, G., Rizzardo, E.; Thang, S.H.,** 1998, Living free-radical polymerization by reversible addition-fragmentation chain transfer: The RAFT process, *Macromolecules*, **31,** 5559-5562.

[52] **Grimaud, T.; Matyjaszewski, K.,** 1997. Controlled/"Living" radical polymerization of methyl methacrylate by atom transfer radical polymerization, *Macromolecules*, **30**, 2216.

[53] **Patten, T.E.; Matyjaszewski, K.,** 1999, Copper(I)-catalyzed atom transfer radical polymerization, *Accounts of Chemical Research*, **32,** 895-903.

[54] **Matyjaszewski, K.,** 2000. Environmental aspects of controlled radical polymerization, *Macromol. Symp.*, 152, 29-42.

[55] **Patten, T. E.; Xia, J. H.; Abernathy, T.; Matyjaszewski, K.,** 1996. Polymers with very low polydispersities from atom transfer radical polymerization. *Science* 272, (5263), 866-868.

[56] **Matyjaszewski, K.; Coca, S.; Gaynor, S. G.; Wei, M.; Woodworth, B. E.,** 1998. Controlled radical polymerization in the presence of oxygen. *Macromolecules* 31, (17), 5967-5969.

[57] **Beers, K. L.; Matyjaszewski, K.; Woodworth, B.,** 2001. Controlled/living radical polymerization in the undergraduate laboratories. 1. Using atrp to prepare block and statistical copolymers of n-butyl acrylate and styrene. *Journal of Chemical Education* 78, (4), 544-null.

[58] **Matyjaszewski, K.; Beers, K. L.; Metzner, Z.; Woodworth, B.,** 2001. Controlled/living radical polymerization in the undergraduate laboratories. 2. Using atrp in limited amounts of air to prepare block and statistical copolymers of n-butyl acrylate and styrene. *Journal of Chemical Education* 78, (4), 547-null.

[59] **Kickelbick, G.; Paik, H. J..; Matyjaszewski, K.,** 1999. Immobilization of the copper catalyst in atom transfer radical polymerization. *Macromolecules* 32, (9), 2941-2947.

[60] **Haddleton, D. M.; Duncalf, D. J.; Kukulj, D.; Radigue, A. P.,** 1999. 3-aminopropyl silica supported living radical polymerization of methyl methacrylate: Dichlorotris(triphenylphosphine)ruthenium(II) mediated atom transfer polymerization. *Macromolecules* 32, (15), 4769-4775.

[61] **Haddleton, D. M.; Kukulj, D.; Radigue, A. P.,** 1999. Atom transfer polymerisation of methyl methacrylate mediated by solid supported copper catalysts. *Chemical Communications*, (1), 99-100.

[62] **Zhang, X.; Xia, J.; Matyjaszewski, K.,** 1998. Controlled/"living"□ radical polymerization of 2-(dimethylamino)ethyl methacrylate. *Macromolecules* 31, (15), 5167-5169.

[63] **Matyjaszewski, K.; Xia, J. H.,** 2001. Atom transfer radical polymerization. *Chemical Reviews* 101, (9), 2921-2990.

[64] **Haddleton, D. M.; Jasieczek, C. B.; Hannon, M. J.; Shooter, A. J.,** 1997. Atom transfer radical polymerization of methyl methacrylate initiated by alkyl bromide and 2-pyridinecarbaldehyde imine copper(I) complexes. *Macromolecules* 30, (7), 2190-2193.

[65] **Matyjaszewski, K.; Shipp, D. A.; Qiu, J.; Gaynor, S. G.,** 2000. Water-borne block and statistical copolymers synthesized using atom transfer radical polymerization. *Macromolecules* 33, (7), 2296-2298.

[66] **Granel, C.; Dubois, P.; Jerome, R.; Teyssie, P.,** 1996. Controlled radical polymerization of methacrylic monomers in the presence of a bis(ortho-chelated) arylnickel(II) complex and different activated alkyl halides. *Macromolecules* 29, (27), 8576-8582.

[67] **Uegaki, H.; Kotani, Y.; Kamigaito, M.; Sawamoto, M.,** 1998. Nibr2(pn-bu3)2-mediated living radical polymerization of methacrylates and acrylates and their block or random copolymerizations1. *Macromolecules* 31, (20), 6756-6761.

[68] **Moineau, C.; Minet, M.; Teyssie, P.; Jerome, R.,** 1999. Synthesis and characterization of poly(methyl methacrylate)-block-poly(n-butyl acrylate)-block-poly(methyl methacrylate) copolymers by two-step controlled radical polymerization (atrp) catalyzed by nibr2(pph3)(2), - 1. *Macromolecules* 32, 8277-8282.

[69] **Ando, T.; Kamigaito, M.; Sawamoto, M.,** 1997. Iron(II) chloride complex for living radical polymerization of methyl methacrylate. *Macromolecules* 30, (16), 4507-4510.

[70] **Louie, J.; Grubbs, R. H.,** 2000. Highly active iron imidazolylidene catalysts for atom transfer radical polymerization. *Chemical Communications*, (16), 1479-1480.

[71] **Lecomte, P.; Drapier, I.; Dubois, P.; Teyssie, P.; Jerome, R.,** 1997. Controlled radical polymerization of methyl methacrylate in the presence of palladium acetate, triphenylphosphine, and carbon tetrachloride. *Macromolecules* 30, (24), 7631-7633.

[72] **Moineau, G.; Granel, C.; Dubois, P.; Jerome, R.; Teyssie, P.,** 1998. Controlled radical polymerization of methyl methacrylate initiated by an alkyl halide in the presence of the wilkinson catalyst. *Macromolecules* 31, (2), 542-544.

[73] **Destarac, M.; Matyjaszewski, K.; Boutevin, B.,** 2000. Polychloroalkane initiators in copper-catalyzed atom transfer radical polymerization of (meth)acrylates. *Macromolecular Chemistry and Physics* 201, (2), 265-272.

[74] **Destarac, M.; Boutevin, B.; Matyjaszewski, K.,** 2000. Polychloroalkanes as atrp initiators: Fundamentals and application to the synthesis of block copolymers from the combination of conventional radical polymerization and atrp. In *Controlled/living radical polymerization*, American Chemical Society: Vol. 768, pp 234-247.

[75] **Kotani, Y.; Kato, M.; Kamigaito, M.; Sawamoto, M.**, 1996. Living radical polymerization of alkyl methacrylates with ruthenium complex and synthesis of their block copolymers1. *Macromolecules* 29, (22), 6979-6982.

[76] **Zhang, X.; Xia, J. H.; Matyjaszewski, K.**, 1998. Controlled/"Living" Radical polymerization of 2-(dimethylamino)ethyl methacrylate. *Macromolecules* 31, (15), 5167-5169.

[77] **Beers, K. L.; Boo, S.; Gaynor, S. G.; Matyjaszewski, K.**, 1999. Atom transfer radical polymerization of 2-hydroxyethyl methacrylate. *Macromolecules* 32, (18), 5772-5776.

[78] **Beers, K. L.; Gaynor, S. G.; Matyjaszewski, K.; Sheiko, S. S.; Moller, M.**, 1998, The synthesis of densely grafted copolymers by atom transfer radical polymerization. *Macromolecules* 31, (26), 9413-9415.

[78] **Xia, J. H.; Zhang, X.; Matyjaszewski, K.**, 2000. In *Transition metal catalysis in macromolecular design;*, L. S. Boffa, B. N., M.,, Ed. ACS Symposium Series 760; American Chemical Society:: Washington, DC, Vol. 13.

[80] **Zhang, X.; Matyjaszewski, K.**, 1999. Synthesis of functional polystyrenes by atom transfer radical polymerization using protected and unprotected carboxylic acid initiators. *Macromolecules* 32, (22), 7349-7353.

[81] **Ashford, E. J.; Naldi, V.; O'Dell, R.; Billingham, N. C.; Armes, S. P.**, 1999. First example of the atom transfer radical polymerisation of an acidic monomer: Direct synthesis of methacrylic acid copolymers in aqueous media. *Chemical Communications*, (14), 1285-1286.

[82] **Matyjaszewski, K.; Mu Jo, S.; Paik, H. J.; Gaynor, S. G.**, 1997. Synthesis of well-defined polyacrylonitrile by atom transfer radical polymerization. *Macromolecules* 30, (20), 6398-6400.

[83] **Matyjaszewski, K.; Gaynor Scott, G.; Qiu, J.; Beers, K.; Coca, S.; Davis, K.; Muhlebach, A.; Xia, J.; Zhang, X.**, 2000. The preparation of well-defined water soluble-swellable (co)polymers by atom transfer radical polymerization. In *Associative polymers in aqueous media*, American Chemical Society: Vol. 765, pp 52-71.

[84] **Matyjaszewski, K.; Ziegler, M. J.; Arehart, S. V.; Greszta, D.; Pakula, T.**, 2000. Gradient copolymers by atom transfer radical copolymerization. *Journal of Physical Organic Chemistry* 13, (12), 775-786.

[85] **Hamley, I. W.,** 1998. The Physics of block copolymers, Oxford University Press, Oxford.

[86] **Hawker,** 1994. Molecular weight control by a "living" free-radical polymerization process**,** *Journal of the American Chemical Society*, **116**, 11185.

[87] **Odian,** 1991. *G. Principles of polymerization,* p 8, *John Wiley & Sons Inc.*

[88] **Harth, E., Hawker, C.J., Fan, W., Waymouth,** 2001**.** Chain end functionalization in nitroxide-mediated "living" free radical Polymerizations**,** *R.M. Macromolecules,* **34**, 3856.

[89] **a) Haddleton, D. M.; Topping, C.; Hastings, J. J.; Suddaby, K. G.,** 1996. **Cobalt(II) in catalytic chain transfer polymerization (CCTP),** *Macromolecules*, **29**, 481. **b) Chong, Y. K., Le, T. P. T., Moad, G., Rizzardo, E.,** 1999, A more versatile route to block copolymers and other polymers of complex architecture by living radical polymerization: The RAFT process, *S. Macromolecules*, **32**, 2071.

[90] **Ben Reeves**, 2001. Recent advances in living free radical polymerization, *University of Florida.*

[91] **Odian, G.**, 1991. In *Principles of polymerization*, John Wiley & Sons: New York.

[92] **Bielawski, C. W.; Grubbs, R. H.**, 2007, Living ring-opening metathesis polymerization, *Progress in Polymer Science*, **32,** 1-29.

[93] **Dragutan V.; Dragutan I.; Balaban A.T.**, 2006, "Nobel Prize 2005 in chemistry for the metathesis reaction", Awarded for the development of the metathesis reaction in organic synthesis**,** *Platinum Metals Review*, **50(1),** 35-37.

[94] **Kolb, H.C.; Finn, M.G.; Sharpless, K.B.**, 2001, Click chemistry: Diverse chemical function from a few good reactions, *Angewandte Chemie-International Edition*, **40,** 2004-2021.

[95] **Diels, O.; Alder, K.**, 1928, Synthesen in der hydroaromatischen Reihe, *Justus Liebig's Annalen der Chemie*, **460,** 98-122.

[96] **Corey, E.J.**, 2002, Catalytic enantioselective Diels-Alder reactions: Methods, mechanistic fundamentals, pathways, and applications, *Angewandte Chemie-International Edition*, **41,** 1650-1667.

[97] **Diels, O.; Alder, K.**, 1926, Über die Ursachen der Azoesterreaktion, *Justus Liebig's Annalen der Chemie*, **450,** 237-254.

[98] **Fringuelli, F.; Taticchi, A.**, 2002. *The Diels Alder reaction : selected practical methods*. Chichester, New York, Wiley.

[99] **Woodward, R.B.; Hoffmann, R.**, 1970. *The conservation of orbital symmetry*. Weinheim/Bergstr, Verlag Chemie.

[100] **Woodward, R.B.; Hoffmann, R.**, 1965, Stereochemistry of electrocyclic reactions, *Journal of the American Chemical Society*, **87,** 395-397.

[101] **Kolb, H. C.; Sharpless, K. B.,** 2003. The growing impact of click chemistry on drug discovery, *DDT*, **8**, 1128-1137.

[102] **Gacal, B.; Durmaz, H.; Tasdelen, M. A.; Hizal, G.; Tunca, U.; Yagci, Y.; Demirel, A. L.,** 2006. Anthracene-Maleimide-Based Diels Alder "Click Chemsitry" as a Novel Route to Graft Copolymers, *Macromolecules*, **39**, 5330-5336.

[103] **Bock, V. D.; Hiemstra, H.; Van Maarseveen, J. H.,** 2006. Cu(I)-Catalyzed Alkyne-Azide "Click" Cycloadditions from a Mechanistic and Synthetic Perspective, *Eur. J. Org. Chem.*, 51-68.

[104] **Liu, Q.; Chen, Y.,** 2006. Synthesis of Well-Defined Macromonomers by the Combination of Atom Transfer Radical Polymerization and a Click Reaction, *Journal of Polymer Science: Part A: Polymer Chemistry*, **44**, 6103-6113.

[105] **Lutz, J. F.; Börner, H. G.; Weichencan, K.,** 2005. Combining Atom Transfer Radical Polymerization and Click Chemistry: A Versatile Method for the Preparation of End-Functional Polymers, *Macromol. Rapid Commun.*, **26**, 514-518.

[106] **Kamijo, S.; Jinb, T.; Yamamotoa, Y.,** 2004. Four-component coupling reactions of silylacetylenes, allyl carbonates, and trimethylsilyl azide catalyzed by a Pd(0)-Cu(I) bimetallic catalyst. Fully substituted triazole synthesis from seemingly internal alkynes, *Tetrahedron Letters*, **45**, 689-691.

[107] **Hotha, S.; Anegundi, R. ; Natu, A. A.,** 2005. Expedient synthesis of 1,2,3 triazole-fused tetracyclic compounds by intramolecular Huisgen (click) reactions on carbohydrate-derived azido-alkynes, *Tetrahedron Letters*, **46**, 4585-4588.

[108] **Fu, Q.; Wang, G.; Lin, W.; Huang, J.,** 2009. , One-Pot Preparation of 3 Miktoarm Star Terpolymers via ‘‘Click Chemistry’’ and Atom Transfer Nitroxide Radical Coupling Reaction, J. Polym. Sci., Part A: Polym. Chem., 47, (3), 986–990.

[109] **Luo, X.; Wang, G.; Huang, J**., 2008. Preparation of H-shaped ABCAB terpolymers by atom transfer radical coupling, J. Polym. Sci., Part A: Polym. Chem., 47, (1), 59–68.

[110] **Fu, Q.; Liu, C.; Lin, W.; Huang, J.,** 2008. One-Pot Synthesis of Heterograft Copolymers via ‘‘Graft Onto’’ by Atom Transfer Nitroxide Radical Coupling Chemistry, J. Polym. Sci., Part A: Polym. Chem., 46, (20), 6770–6779.

[111] **Liu, C.; Pan, M.; Zhang, Y.; Huang, J.,** 2008. Preparation of star block copolymers with polystyrene-block-poly(ethylene oxide) as side chains on hyperbranched polyglycerol core by combination of ATRP with atom transfer nitroxide radical coupling reaction, J. Polym. Sci., Part A: Polym. Chem., 46, (20), 6754–6761.

[112] **Lin, W.; Fu, Q.; Zhang, Y.; Huang, J.,** 2008. One-Pot Synthesis of ABC Type Triblock Copolymers via a Combination of “Click Chemistry” and Atom Transfer Nitroxide Radical Coupling Chemistry, Macromolecules, 41 (12), 4127–4135.

[113] **Fu, Q.; Lin, W.; Huang, J.,** 2008. A New Strategy for Preparation of Graft Copolymers via “Graft onto” by Atom Transfer Nitroxide Radical Coupling Chemistry: Preparation of Poly(4-glycidyloxy-2,2,6,6-tetramethylpiperidine-1-oxyl-*co*-ethylene oxide)-*graft*-polystyrene and Poly(*tert*-butyl acrylate), Macromolecules, 41 (7), 2381–2387.

[114] **Nicolay, R.; Marx, L.; Hemery, P.; Matyjaszewski, K.,** 2007. Synthesis of Multisegmented Degradable Polymers by Atom Transfer

Radical Cross-Coupling, Macromolecules, 40, (26), 9217–9223.

[115] **Matyjaszewski, K.; Woodworth, B. E.; Zhang, X.; Gaynor, S. G.; Metzner, Z**., 1998. Simple and Efficient Synthesis of Various Alkoxyamines for Stable Free Radical Polymerization, Macromolecules, 31, 5955–5957.

[116] **Otsuka, H.; Aotani, K.; Higaki, Y.; Takahara, A.**, 2002.Chem. Commun., 2838–2839.

[117] **Otsuka, H.; Aotani, K.; Higaki, Y.; Takahara, A. J**.,2003. Am. Chem. Soc., 125, 4064–4065.

[118] **Higaki, Y.; Otsuka, H.; Takahara, A**.,2004. Macromolecules, 37, 1696–1701.

[119] **Gao, C.; Yan, D.**, 2004. Hyperbranched polymers: From synthesis to applications. *Progress in Polymer Science* 29, (3), 183-275.

[120] **Teertstra, S. J.; Gauthier, M.**, 2004. Dendrigraft polymers: Macromolecular engineering on a mesoscopic scale. *Progress in Polymer Science* 29, (4), 277-327.

[121] **Wang, C. C.; Guo, Z. X.; Fu, S. K.; Wu, W.; Zhu, D. B.**, 2004. Polymers containing fullerene or carbon nanotube structures. *Progress in Polymer Science* 29, (11), 1079-1141.

[122] **Hadjichristidis, N.**, 2003. Polymer chemists/polymer physicists: A constructive partnership. *European Physical Journal E* 10, (1), 83-86.

[123] **Davis, K. A.; Matyjaszewski, K.**, 2002. Statistical, gradient, block, and graft copolymers by controlled/living radical polymerizations. *Advances in Polymer Science* 159, 1-169.

[124] **Mori, H.; Muller, A. H. E.**, 2003. New polymeric architectures with (meth)acrylic acid segments. *Progress in Polymer Science* 28, (10), 1403-1439.

[125] **Kobayashi , S.,** 2008. New frontiers in polymer synthesis. *Advances in Polymer Science* 123-125.

[126] **Ruehl, J.K.; Cruz S.,** 2008. Alkoxyamine initiators for nitroxidemediatedradical polymerization 193-196.

[127] **Altintas, O.; Hizal, G.; Tunca, U.,** 2009. Synthesis of an ABCD 4-miktoarm Star Quaterpolymer through a Diels-Alder Click Reaction, Designed Monomers and Polymers, 12, 83-98.

[128] **Durmaz, H.; Dag, A.; Hizal, G.; Tunca, U.,** 2010. Cyclic Homo and Block Copolymers Through Sequential Double Click Reactions, *J. Polym Sci Part A: Polym Chem* 48, 5083-5091.

[129] **Roovers, J.; Toporowski, P. M.,** 1983. Synthesis of high molecular weight ring polystyrenes, M. Macromolecules, 16, 843–849.

[130] **Lepoittevin, B. Dourges, M. A.; Masure, M.; Hemery, P.; Baran, K.; Cramail, H.,** 2000. *Macromolecules, 33*, 8218-8224.

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